

# LOAN DOCUMENT

<p style="writing-mode: vertical-rl; transform: rotate(180deg);">DTIC ACCESSION NUMBER</p>	<p>PHOTOGRAPH THIS SHEET</p> <div style="border: 1px solid black; width: 100px; height: 80px; margin: 0 auto;"></div> <p>LEVEL</p>	<p>INVENTORY</p> <div style="border: 1px solid black; width: 50px; height: 50px; display: flex; align-items: center; justify-content: center; margin: 0 auto;"> <span style="font-size: 2em;">0</span> </div>																												
<p><i>Corrective Action Plan for the Risk...</i></p> <p>DOCUMENT IDENTIFICATION</p> <p><i>Mar 97</i></p>																														
<p><b>DISTRIBUTION STATEMENT A</b></p> <p>Approved for Public Release</p> <p>Distribution Unlimited</p>																														
<p>DISTRIBUTION STATEMENT</p>																														
<table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="2">ACCESSION FOR</td> </tr> <tr> <td>NTIS</td> <td>GRAB <input checked="" type="checkbox"/></td> </tr> <tr> <td>DTIC</td> <td>TRAC <input type="checkbox"/></td> </tr> <tr> <td>UNANNOUNCED</td> <td><input type="checkbox"/></td> </tr> <tr> <td>JUSTIFICATION</td> <td></td> </tr> <tr><td colspan="2"> </td></tr> <tr><td colspan="2"> </td></tr> <tr><td colspan="2"> </td></tr> <tr><td colspan="2"> </td></tr> <tr><td colspan="2">BY</td></tr> <tr><td colspan="2">DISTRIBUTION/</td></tr> <tr><td colspan="2">AVAILABILITY CODES</td></tr> <tr> <td>DISTRIBUTION</td> <td>AVAILABILITY AND/OR SPECIAL</td> </tr> <tr> <td style="height: 50px; vertical-align: middle; font-size: 2em;">A-1</td> <td></td> </tr> </table>	ACCESSION FOR		NTIS	GRAB <input checked="" type="checkbox"/>	DTIC	TRAC <input type="checkbox"/>	UNANNOUNCED	<input type="checkbox"/>	JUSTIFICATION										BY		DISTRIBUTION/		AVAILABILITY CODES		DISTRIBUTION	AVAILABILITY AND/OR SPECIAL	A-1		<div style="border: 1px solid black; width: 100%; height: 150px; margin-bottom: 10px;"></div> <p style="text-align: center;">DATE ACCESSIONED</p> <div style="border: 1px solid black; width: 100%; height: 100px; margin-bottom: 10px;"></div> <p style="text-align: center;">DATE RETURNED</p> <div style="border: 1px solid black; width: 100%; height: 100px;"></div> <p style="text-align: center;">REGISTERED OR CERTIFIED NUMBER</p>	
ACCESSION FOR																														
NTIS	GRAB <input checked="" type="checkbox"/>																													
DTIC	TRAC <input type="checkbox"/>																													
UNANNOUNCED	<input type="checkbox"/>																													
JUSTIFICATION																														
BY																														
DISTRIBUTION/																														
AVAILABILITY CODES																														
DISTRIBUTION	AVAILABILITY AND/OR SPECIAL																													
A-1																														
<p>DISTRIBUTION STAMP</p>																														
<div style="border: 1px solid black; width: 100%; height: 80px; display: flex; align-items: center; justify-content: center;"> <p style="font-size: 1.5em;">DTIC QUALITY INSPECTED 4</p> <p style="font-size: 2em; margin-left: 10px;">20010117 017</p> </div>																														
<p>DATE RECEIVED IN DTIC</p>																														
<p>PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC</p>																														

HANDLE WITH CARE

**FINAL**  
**Corrective Action Plan**  
**for the Risk-Based**  
**Remediation of the MOGAS Site**



**Myrtle Beach Air Force Base**  
**South Carolina**

**Volume I of II**

**Prepared For**

**Air Force Center for Environmental Excellence**  
**Technology Transfer Division**  
**Brooks Air Force Base**  
**San Antonio, Texas**

**and**

**Myrtle Beach Air Force Base**  
**South Carolina**

**March 1997**

DEFENSE TECHNICAL INFORMATION CENTER  
REQUEST FOR SCIENTIFIC AND TECHNICAL REPORTS

Title

AFCEE Collection

## 1. Report Availability (Please check one box)

- ☒ This report is available. Complete sections 2a - 2f.  
☐ This report is not available. Complete section 3.

2a. Number of  
Copies Forwarded

1 each

## 2b. Forwarding Date

July/2000

## 2c. Distribution Statement (Please check ONE box)

DoD Directive 5230.24, "Distribution Statements on Technical Documents," 18 Mar 87, contains seven distribution statements, as described briefly below. Technical documents MUST be assigned a distribution statement.

- ☒ DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.
- ☐ DISTRIBUTION STATEMENT B: Distribution authorized to U.S. Government Agencies only.
- ☐ DISTRIBUTION STATEMENT C: Distribution authorized to U.S. Government Agencies and their contractors.
- ☐ DISTRIBUTION STATEMENT D: Distribution authorized to U.S. Department of Defense (DoD) and U.S. DoD contractors only.
- ☐ DISTRIBUTION STATEMENT E: Distribution authorized to U.S. Department of Defense (DoD) components only.
- ☐ DISTRIBUTION STATEMENT F: Further dissemination only as directed by the controlling DoD office indicated below or by higher authority.
- ☐ DISTRIBUTION STATEMENT X: Distribution authorized to U.S. Government agencies and private individuals or enterprises eligible to obtain export-controlled technical data in accordance with DoD Directive 5230.25, Withholding of Unclassified Technical Data from Public Disclosure, 6 Nov 84.

## 2d. Reason For the Above Distribution Statement (in accordance with DoD Directive 5230.24)

## 2e. Controlling Office

HQ AFCEE

2f. Date of Distribution Statement  
Determination

15 Nov 2000

## 3. This report is NOT forwarded for the following reasons. (Please check appropriate box)

- ☐ It was previously forwarded to DTIC on \_\_\_\_\_ (date) and the AD number is \_\_\_\_\_
- ☐ It will be published at a later date. Enter approximate date if known. \_\_\_\_\_
- ☐ In accordance with the provisions of DoD Directive 3200.12, the requested document is not supplied because: \_\_\_\_\_

Print or Type Name

Laura Peña

Telephone

210-536-1431

Signature

Laura Peña

(For DTIC Use Only)

AQ Number MDI-04-0640

**FINAL**

**CORRECTIVE ACTION PLAN**

**FOR THE RISK-BASED REMEDIATION OF THE MOGAS SITE**

**VOLUME I OF II**

**MYRTLE BEACH AIR FORCE BASE**  
**SOUTH CAROLINA**

**March 1997**

**Prepared for**

**Air Force Center for Environmental Excellence**  
**Brooks Air Force Base**  
**San Antonio, Texas**

**and**

**Myrtle Beach Air Force Base, South Carolina**

**Prepared by**  
**Parsons Engineering Science, Inc.**  
**Denver, Colorado**

ADMOI-04-0640

## EXECUTIVE SUMMARY

### General Overview

A comprehensive site investigation addressing soil, groundwater, surface water, and sediment contaminated with fuel hydrocarbons at the Motor Gasoline (MOGAS) Storage Area, Myrtle Beach Air Force Base (AFB), South Carolina, was conducted by Parsons Engineering Science, Inc. (Parsons ES). Field work was conducted to complete the corrective action plan (CAP) presented in this report in support of a risk-based remediation decision for the MOGAS site. Characterization field efforts for this investigation were conducted from January through September 1995. Selected source reduction technologies were field-tested at the MOGAS site from November 1995 to January 1996 to determine the effectiveness of these remedial techniques in treating site-related contamination.

The risk-based remediation demonstration at the MOGAS site is sponsored by the United States (US) Air Force Center for Environmental Excellence (AFCEE) at Brooks AFB, Texas under contract F41624-93-C-8044, and is a component of a multi-site AFCEE initiative. The purpose of this initiative is to demonstrate how quantitative fate and transport calculations and risk evaluation, based on site-specific data, can be integrated. Consequently, this integration allows for rapid determination of the type and magnitude of corrective action required at a site to minimize contaminant migration, receptor exposure, and subsequent risks to the potential receptors. Risk-based remediation is designed to combine natural physical, chemical, and biological processes with low-cost source reduction technologies such as *in situ* bioventing, as necessary, to economically reduce potential risks to human health and the environment posed by subsurface petroleum fuel spills.

The MOGAS site is located in the northwestern quadrant of the Base. Three 5,000-gallon underground storage tanks (USTs) were used to store gasoline at the site, and one 5,000-gallon UST was used for diesel fuel storage. The USTs were removed in 1993. Historical releases from at least two of these tanks have contaminated soil and groundwater with fuel hydrocarbons. Contaminated groundwater discharges to a man-made drainage ditch along the southern edge of the MOGAS site, resulting in surface water and sediment contamination. Free product was observed on the groundwater surface in the 1980s; however measurable free product has not been observed in site monitoring wells during the 1990s.

The CAP for the MOGAS site follows South Carolina Department of Health and Environmental Control (SCDHEC, 1995) guidance for implementing risk-based corrective actions in the state. The guidance outlines a tiered approach for establishing corrective action requirements at specific sites. The tiered approach is based on an evaluation of potentially completed receptor exposure pathways from contaminated site media under both current and future land use scenarios.

One objective of the CAP is to document any potential current risks to human health and the environment (i.e., ecological receptors) due to exposure to chemical

contaminants originating from the MOGAS site. The CAP also addresses the potential future risks to human and ecological receptors due to exposure to chemical contaminants over time, accounting for the effects of natural chemical attenuation processes. The overall objective of the CAP is to develop and present a recommended risk-based remedial approach for fuel hydrocarbon contamination in soils, groundwater, and surface water at the MOGAS site that is protective of both human health and the environment.

### **Overview of Project Activities**

It is the intent of the Air Force to pursue a site-specific, risk-based remediation of the MOGAS site in conformance with the tiered-approach framework established by SCDHEC (1995). The activities conducted pursuant to 1) classifying the release, 2) determining the need for and type of any interim corrective action, and 3) establishing the level of evaluation necessary to define risk-reduction requirements at this site included characterizing:

- The nature and extent of fuel hydrocarbon contamination at the site;
- The locations of potential groundwater recharge and discharge areas;
- The local geology, hydrogeology, and hydrology that may affect contaminant transport;
- The proximity of the site to drinking water aquifers, surface water, and other sensitive environmental resources;
- The expected persistence, mobility, chemical form, and environmental fate of contaminants in soils and groundwater under the influence of natural physical, chemical, and biological processes;
- The current and potential future uses of the site and its vicinity, including groundwater, and the likelihood of exposure of receptors to other potentially impacted environmental media over time;
- The potential risks associated with chemical contamination under current and foreseeable future conditions;
- The long-term target remedial objectives and chemical-specific concentration goals required to protect human health and the environment; and
- The treatability of residual and dissolved fuel hydrocarbon contamination using low-cost source-reduction technologies such as air sparging, bioventing, and soil vapor extraction (SVE).

### **Results of Risk-Based Analysis**

Several remedial approaches that rely both on natural processes and on engineered solutions were evaluated for the site. A site-specific exposure pathways analysis involving environmental media impacted by chemical contamination at and migrating

from the MOGAS site was completed to assess whether existing and predicted future concentrations of hazardous substances would pose a threat to current and foreseeable future onsite or offsite receptors. The site-specific exposure pathway analysis indicates that only onsite intrusive workers and potential surface water receptors (i.e., trespassers/recreators and transient wildlife) could reasonably be exposed to significant concentrations of site-related contamination.

Concentrations of several fuel hydrocarbons measured at the MOGAS site exceed applicable Tier 1 risk-based screening levels (RBSLs) (SCDHEC, 1995). Tier 1 RBSLs are generic or nonsite-specific risk-based concentrations that are used as a screening tool to initially determine chemicals of potential concern (COPCs). The analytes with MOGAS site concentrations above the Tier 1 screening levels include:

- Benzene, toluene, ethylbenzene, xylenes (BTEX);
- Naphthalene;
- Chlorobenzene; and
- 1,2,4 and 1,3,5-Trimethylbenzene (1,2,4-TMB and 1,3,5-TMB).

Consequently, a comprehensive Tier 2 evaluation was conducted to (1) develop alternate site-specific target levels (SSTLs) to be used to guide the type, magnitude, and timing of corrective action to be implemented at the site, (2) determine whether any unacceptable and imminent threats to human health or the environment exist at the site, and (3) select and prepare an initial design of the recommended corrective action, including land use controls, and a long-term monitoring plan (LTMP) to protect human health and the environment.

Comparison of MOGAS site contaminant concentrations to site-specific Tier 2 SSTLs indicated that the maximum detected concentrations of benzene, ethylbenzene, and naphthalene measured in groundwater in 1995 exceeded their respective health-based groundwater SSTLs. In addition, the maximum detected 1995 concentration of benzene in surface water exceeded the SSTLs computed for that medium. Average contaminant concentrations in soils did not exceed soil leaching SSTLs, indicating that leaching would not result in sustained groundwater contamination above the groundwater SSTLs.

A site-specific chemical fate assessment was completed as part of the Tier 2 quantitative exposure pathways analysis to identify the potential for, and risks associated with, receptor exposure to chemical contamination over time at the site. The potential for receptor exposure to chemical contamination originating from the MOGAS site over time depends on future site conditions and the persistence, mobility, chemical form, toxicity, and fate of site-related contaminants. Site characterization data relevant to documenting natural chemical attenuation, specifically bioattenuation, were collected and are documented in this CAP. Fate and transport model results were used to predict the exposure-point concentrations of an indicator compound (benzene) over time at the site.

Based upon the Tier 2 assessment and evaluation, the MOGAS site is classified as a Category 5 release. Although chemicals of potential concern (COPCs) are expected to persist in groundwater and surface water at concentrations above health-protective SSTLs for many years without some form of engineered remediation, a Category 5 classification is warranted because aquatic life RBSLs were not exceeded, and no other exposure pathways are likely to be completed due to the absence of human receptors. The presence of asphalt paving, lack of intrusive activities, and the unlikelihood that recreators/trespassers will be present in the ditch where elevated benzene concentrations persist minimize the potential for unacceptable exposure.

Although site-specific data indicate that groundwater COPCs are being reduced in mass, concentration, and toxicity by natural chemical attenuation processes, the Bioplume II model developed for the MOGAS site suggests that concentrations of dissolved benzene, an indicator groundwater COPC, will not be reduced below its Tier 2 groundwater SSTL at every point at the site until the year 2085 unless some type of engineered remediation is undertaken. Additionally, this model predicts that benzene could continue to discharge into the drainage ditch at concentrations above the Tier 2 surface water SSTL for approximately 110 years. Therefore, attainment of Tier 2 SSTLs in both groundwater and surface water could not be demonstrated for at least 90 years if only natural chemical attenuation with long-term monitoring were implemented at this site. The Air Force recognizes that this is not a reasonable corrective action time frame. Consequently, some form of engineered remediation is warranted to supplement the benefits of natural chemical attenuation processes and land use controls.

### **Recommended Remedial Alternative**

Three remedial alternatives were developed to more rapidly achieve the desired contaminant reductions. The comparative remedial analysis presented in this CAP shows that the best combination of risk reduction and low cost remediation can be achieved by implementing air sparging of dissolved contaminants in groundwater, with resulting concurrent, incidental bioventing of residual contamination in the capillary fringe and vadose zone. Air sparging in the source area would expedite reductions in volatile organic contaminant concentrations in the vadose zone, capillary fringe, and saturated soils, and construction of an air sparging curtain along the upgradient bank of the drainage ditch would substantially reduce discharge of contaminants to the ditch. Simulation of this remedial alternative using the Bioplume II model suggests that this system would achieve health-protective Tier 2 SSTLs for groundwater and surface water within 4 years of continuous operation (i.e., from the year 1997 to the year 2001). The use of low-cost source reduction technologies decreases the length of time required to achieve Tier 2 SSTLs in all media at minimal cost. To confirm that the predicted degree of remediation is being attained and to ensure that no unacceptable receptor exposures to chemical contamination could occur at the site, a LTMP is included in this CAP.

## TABLE OF CONTENTS

	<u>Page</u>
List of Acronyms and Abbreviations .....	ix
EXECUTIVE SUMMARY .....	ES-1
 SECTION 1 - INTRODUCTION .....	 1-1
1.1 Purpose and Scope .....	1-1
1.2 Report Organization .....	1-3
1.3 Mogas Site Description and Operational History .....	1-3
1.4 Results of Previous Remedial Investigations Reformat .....	1-9
1.4.1 Soil Gas .....	1-9
1.4.2 Soils .....	1-10
1.4.3 Groundwater .....	1-11
1.4.4 Free Product .....	1-11
1.4.5 Surface Water .....	1-12
1.4.6 Stream Sediment .....	1-12
 SECTION 2 - SITE CHARACTERIZATION ACTIVITIES .....	 2-1
2.1 Scope of Data Collection Activities .....	2-1
2.2 Phase I - Initial Site Characterization Screening .....	2-4
2.2.1 Cone Penetrometer Testing and Monitoring Point Installation .....	2-4
2.2.2 Groundwater Sampling .....	2-12
2.3 Phase II - Supplemental Site Characterization Sampling .....	2-16
2.3.1 Subsurface Soil Sampling .....	2-16
2.3.2 Monitoring Well Installation .....	2-17
2.3.3 Well Development .....	2-17
2.3.4 Groundwater Sampling .....	2-19
2.3.5 Aquifer Testing .....	2-19
2.3.6 Surface Water and Sediment Sampling .....	2-20
2.3.7 Surveying .....	2-21
2.3.8 Investigation-Derived Wastes .....	2-21
2.4 Phase III - Source Reduction Pilot Testing .....	2-21
2.4.1 Soil Gas Measurements .....	2-21
2.4.2 Source Reduction Treatability Testing .....	2-22
2.5 Analytical Data Quality and Management .....	2-23

## TABLE OF CONTENTS (Continued)

SECTION 3 - PHYSICAL CHARACTERISTICS OF THE STUDY AREA.....	3-1
3.1 Regional Topography and Surface Water Hydrology .....	3-1
3.2 Regional Geology and Hydrogeology .....	3-2
3.2.1 Regional Geology .....	3-2
3.2.2 Regional Hydrogeology .....	3-3
3.3 Site Land Use, Topography, and Surface Water Hydrology .....	3-3
3.4 Site Geology and hydrogeology .....	3-5
3.4.1 Lithology and Stratigraphic Relationships .....	3-5
3.4.2 Hydrogeology .....	3-6
3.4.2.1 Groundwater Flow and Gradients .....	3-6
3.4.2.2 Hydraulic Conductivity .....	3-14
3.4.2.3 Effective Porosity .....	3-16
3.4.2.4 Advective Groundwater Velocity.....	3-16
3.4.2.5 Groundwater Recharge .....	3-16
3.5 Climatological Characteristics .....	3-16
3.6 Land Use .....	3-17
3.6.1 Site Access .....	3-17
3.6.2 Current and Proposed Land Use .....	3-17
3.6.3 Water Resources .....	3-17
3.7 Population Demographics .....	3-18
3.8 Ecological Resources .....	3-18
SECTION 4 - TIER 1 ANALYSIS AND IDENTIFICATION OF CHEMICALS OF POTENTIAL CONCERN .....	4-1
4.1 Regulatory Overview of the Tiered Approach.....	4-1
4.1.1 Site Prioritization .....	4-1
4.1.2 Description of the Tier 1 Process .....	4-3
4.2 Preliminary Conceptual Site Model Review .....	4-4
4.3 Tier 1 Screening Analysis .....	4-8
4.3.1 Selection of Appropriate Tier 1 Soil, Groundwater, Air, and Surface Water RBSLs .....	4-8
4.3.1.1 RBSLs for Soil.....	4-9
4.3.1.2 RBSLs for Groundwater .....	4-11
4.3.1.3 RBSLs for Air .....	4-11
4.3.1.4 RBSLs for Surface Water.....	4-11
4.3.2 Screening to Identify COPCs in Soils, Groundwater, Soil Gas, and Surface Water.....	4-16
4.4 Summary of the Mogas Site COPCS .....	4-16
4.5 Site Priority Classification and Tier 1 Action Decision .....	4-25

## TABLE OF CONTENTS (Continued)

SECTION 5 - NATURE AND EXTENT OF CHEMICALS OF POTENTIAL CONCERN.....		5-1
5.1	Overview .....	5-1
5.2	Sources of Contamination .....	5-1
5.3	Soil Vapor Sampling Results.....	5-1
5.4	Soil Sampling Results .....	5-4
5.5	Groundwater Sampling Results.....	5-14
5.5.1	LNAPL .....	5-14
5.5.2	Shallow Dissolved Contamination .....	5-14
5.5.3	Surface Water and Sediment Quality .....	5-20
5.6	Summary .....	5-23
SECTION 6 - TIER 2 QUANTITATIVE CHEMICAL FATE ASSESSMENT .....		6-1
6.1	Introduction .....	6-1
6.2	Operative Mechanisms of Contaminant Attenuation.....	6-1
6.2.1	Chemical Characteristics and Mass Transport Mechanisms.....	6-2
6.2.1.1	Solubility.....	6-2
6.2.1.2	Sorptive Properties.....	6-3
6.2.1.3	Volatility.....	6-3
6.2.1.4	Aquatic Fate.....	6-4
6.2.1.5	Discussion .....	6-4
6.2.2	Biodegradation of COPCs .....	6-5
6.3	Evidence of Contaminant Biodegradation Over Time and Distance .....	6-6
6.3.1	Evidence of COPC Leaching from Soils .....	6-7
6.3.2	Observed Contaminant Loss from Groundwater .....	6-7
6.3.3	Estimating Site-Specific Contaminant Biodegradation Rates .....	6-10
6.4	Evidence of Contaminant Biodegradation Via Microbially Catalyzed Redox Reactions .....	6-11
6.4.1	Relevance of Redox Couples in Biodegradation.....	6-12
6.4.2	Dissolved Oxygen Concentrations .....	6-15
6.4.3	Dissolved Nitrate and Nitrite Concentrations .....	6-18
6.4.4	Ferrous Iron Concentrations .....	6-19
6.4.5	Sulfate Concentrations .....	6-19
6.4.6	Methane and Carbon Dioxide Concentrations .....	6-21
6.5	Theoretical Assimilative Capacity Estimates.....	6-22
6.6	Predicting Contaminant Transport and Fate.....	6-25
6.6.1	Volatilization from Subsurface Sources .....	6-26
6.6.2	Estimating Leaching of COPCs from Saturated Soils .....	6-29
6.6.3	Predicting Fate and Transport of Dissolved Benzene .....	6-30
6.7	Conclusions .....	6-34

## TABLE OF CONTENTS (Continued)

SECTION 7 - TIER 2 ANALYSIS AND IDENTIFICATION OF FINAL CHEMICALS OF CONCERN .....	7-1
7.1 Summary of the Tier 2 Evaluation.....	7-1
7.2 Overview of the Tier 2 Process .....	7-1
7.3 Revised Conceptual Site Model Review .....	7-3
7.3.1 Revised Conceptual Model.....	7-4
7.3.1.1 Sources, Affected Media, Release Mechanisms, and Contaminant Environmental Transport.....	7-4
7.3.1.2 Potentially Exposed Receptors, Exposure Points, and Exposure Routes.....	7-6
7.3.2 Summary of Completed Exposure Pathways.....	7-8
7.4 Development of Site-Specific Target Levels (SSTLS).....	7-8
7.4.1 SSTLs for Soil.....	7-9
7.4.2 SSTLs for Groundwater .....	7-9
7.4.3 SSTLs for Surface Water and Sediment .....	7-9
7.5 Comparison of Exposure-Point Concentrations to SSTLS.....	7-13
7.6 Summary of Risk Reduction Requirements .....	7-17
7.7 Site Priority Classification and Tier 2 Action Decision.....	7-17
SECTION 8 - PILOT TESTING OF SOURCE REDUCTION TECHNOLOGIES .....	8-1
8.1 <i>IN SITU</i> BIOVENTING PILOT TESTING .....	8-1
8.1.1 Vapor Monitoring Point Installation.....	8-1
8.1.2 Respiration Testing .....	8-1
8.2 SVE Pilot Testing.....	8-2
8.2.1 SVE Well Installation .....	8-2
8.2.2 SVE Test Procedures.....	8-2
8.2.3 SVE Test Results .....	8-4
8.2.3.1 Radius of Influence .....	8-4
8.2.3.2 Potential Air Emissions .....	8-4
8.3 Additional Pilot Test Activities.....	8-4
SECTION 9 - DEVELOPMENT OF REMEDIAL ALTERNATIVES.....	9-1
9.1 Summary of Candidate Remedial Alternatives.....	9-2
9.1.1 Need for Engineered Corrective Action .....	9-3
9.1.2 Alternative 1 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, and Air Sparging in the Source Area and Adjacent to the Drainage Ditch .....	9-4
9.1.3 Alternative 2 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, Air Sparging in the Source Area, and Installation of an Oxygen-Release Compound Adjacent to the Drainage Ditch .....	9-5
9.1.4 Alternative 3 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, SVE in the Source Area, and Limited Groundwater Extraction with <i>Ex Situ</i> Treatment .....	9-7

## TABLE OF CONTENTS (Continued)

9.2	Detailed Evaluation of Remedial Alternatives .....	9-10
9.2.1	Summary of Evaluation Criteria .....	9-10
9.2.1.1	Effectiveness .....	9-10
9.2.1.2	Implementability .....	9-10
9.2.1.3	Cost .....	9-10
9.2.2	Alternative 1 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, and Air Sparging in the Source Area and Adjacent to the Drainage Ditch .....	9-11
9.2.2.1	Effectiveness .....	9-11
9.2.2.2	Technical/Administrative Implementability .....	9-16
9.2.2.3	Cost .....	9-18
9.2.3	Alternative 2 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, Air Sparging in the Source Area, and Installation of an Oxygen-Release Compound Adjacent to the Drainage Ditch .....	9-18
9.2.3.1	Effectiveness .....	9-18
9.2.3.2	Technical/Administrative Implementability .....	9-20
9.2.3.3	Cost .....	9-20
9.2.4	Alternative 3 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, SVE in the Source Area, and Limited Groundwater Extraction with <i>Ex Situ</i> Treatment .....	9-22
9.2.4.1	Effectiveness .....	9-22
9.2.4.2	Technical and Administrative Implementability .....	9-23
9.2.4.3	Cost .....	9-24
9.3	Recommendation .....	9-24
SECTION 10 - PROPOSED CORRECTIVE ACTION IMPLEMENTATION PLAN .....		10-1
10.1	Scope of Remedial Activities .....	10-1
10.1.1	Review and Approval of Corrective Action Plan .....	10-1
10.1.2	Air Sparging System Design, Installation, and Operation .....	10-1
10.1.3	Verification of Land and Groundwater Use Controls .....	10-5
10.1.4	Implementation of Groundwater and Surface Water Monitoring .....	10-5
10.2	Implementation Schedule .....	10-8
10.3	Long-Term Monitoring Plan .....	10-8
10.3.1	Biweekly Monitoring of Air Sparging System Operations .....	10-8
10.3.2	Six-Month Testing of Air Sparging System Performance .....	10-10
10.3.3	Subsurface Soil Compliance Sampling .....	10-10
10.3.4	Groundwater and Surface Water Monitoring .....	10-11
10.4	Contingency Plan .....	10-12
10.5	Cost of Implementation .....	10-13
SECTION 11 - REFERENCES .....		11-1

## TABLE OF CONTENTS (Continued)

### LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
Table 2.1	Analyte Reporting Limits .....	2-5
Table 2.2	Phase I Sample Analyses by Location .....	2-8
Table 2.3	Phase II Sample Analyses by Location .....	2-9
Table 2.4	Phase II Sample Analyses by Location .....	2-11
Table 2.5	Drilling and Monitoring Well/Point Installation Summary .....	2-14
Table 3.1	Aquifer Test Results .....	3-15
Table 4.1	Tier 1 Soil Contaminant Screening Criteria .....	4-10
Table 4.2	Tier 1 Soil Leachability Screening Criteria .....	4-12
Table 4.3	Tier 1 Groundwater Contaminant Screening Criteria .....	4-13
Table 4.4	Tier 1 Air Contaminant Screening Criteria .....	4-14
Table 4.5	Tier 1 Surface Water Contaminant Screening Criteria .....	4-15
Table 4.6	Tier 1 Evaluation Comparison of Site Soil Concentration to Direct- Contact RBSLs .....	4-17
Table 4.7	Tier 1 Evaluation Comparison of Site Vadose Zone Soil Concentrations to Direct-Contact RBSLs .....	4-18
Table 4.8	Tier 1 Evaluation Comparison of Site Soil Concentration to Soil Leachability RBSLs .....	4-19
Table 4.9	Tier 1 Evaluation Comparison of Site Groundwater Concentration to Unrestricted Use RBSLs .....	4-20
Table 4.10	Tier 1 Evaluation Comparison of Site Soil Gas Concentration to Inhalation RBSLs .....	4-21
Table 4.11	Tier 1 Evaluation Comparison of Site Surface Water Concentration to RBSLs .....	4-22
Table 4.12	List of Chemicals of Potential Concern .....	4-23
Table 6.1	Estimate of Expressed Assimilative Capacity of Saturated Soil and Groundwater .....	6-24
Table 6.2	Modeling Volatilization from Subsurface Media .....	6-28
Table 6.3	Batch Flushing Model Results .....	6-31
Table 7.1	Site-Specific Target Levels for Soils .....	7-10
Table 7.2	Site-Specific Target Levels for Groundwater .....	7-11
Table 7.3	Site-Specific Target Levels for Surface Water and Sediment .....	7-12
Table 7.4	Comparison of Analytical Soil Data to Soil Leaching SSTLs .....	7-14
Table 7.5	Comparison of Analytical Groundwater Data to Site-Specific Target Levels .....	7-15
Table 7.6	Comparison of Analytical Surface Water Data to Site-Specific Target Levels .....	7-16
Table 8.1	Oxygen Utilization Rates During Initial Bioventing Pilot Testing .....	8-3
Table 8.2	Impact of SVE Pilot Test on Soil Gas Chemistry .....	8-5
Table 9.1	Cost Estimate for Corrective Action Alternative 1 .....	9-19
Table 9.2	Cost Estimate for Corrective Action Alternative 2 .....	9-21
Table 9.3	Cost Estimate for Corrective Action Alternative 3 .....	9-25
Table 10.1	Groundwater/Surface Water Monitoring Analytical Protocol .....	10-6
Table 10.2	Proposed Corrective Action Implementation .....	10-13

## TABLE OF CONTENTS (Continued)

### LIST OF FIGURES

No.	Title	Page
Figure 1.1	Regional Location of Myrtle Beach AFB .....	1-4
Figure 1.2	Site Location and Regional Topography .....	1-6
Figure 1.3	Proximity of Other Fuel Storage Areas to the MOGAS Site .....	1-7
Figure 1.4	Site Layout and Previous Sampling Locations .....	1-8
Figure 2.1	Locations of Phase I Sampling Stations .....	2-13
Figure 2.2	Locations of Phase II Sampling Stations .....	2-18
Figure 3.1	Locations of Hydrogeologic Profiles .....	3-7
Figure 3.2	Hydrogeologic Profile A-A' .....	3-8
Figure 3.3	Hydrogeologic Profile B-B' .....	3-9
Figure 3.4	Shallow Zone Groundwater Elevations August 1995 .....	3-10
Figure 3.5	Deep Zone Groundwater Elevations August 1995 .....	3-11
Figure 3.6	Deep Zone Groundwater Elevations August 1995 .....	3-12
Figure 3.7	Deep Zone Groundwater Elevations October 1995 .....	3-13
Figure 4.1	Overview of SCDHEC Three-Tiered Approach for RBCA for Petroleum Releases .....	4-2
Figure 4.2	Preliminary Conceptual Site Model .....	4-5
Figure 5.1	BTEX Concentrations in Soil Vapor September 1995 .....	5-3
Figure 5.2	TVH Concentrations in Soil Vapor 1995-1996 .....	5-5
Figure 5.3	Maximum Soil BTEX Concentrations 1988-1995 .....	5-7
Figure 5.4	Soil BTEX Concentration Versus Distance from Water Table .....	5-8
Figure 5.5	Maximum Vadose Zone Soil BTEX Concentrations 1988-1995 .....	5-9
Figure 5.6	Chlorobenzene Concentrations in Soil 1988-1995 .....	5-11
Figure 5.7	1,3,5-TMB Concentrations in Soil 1995 .....	5-12
Figure 5.8	Naphthalene Concentrations in Soil 1988-1995 .....	5-13
Figure 5.9	Dissolved BTEX Concentrations in Shallow Groundwater Phase I - January 1995 .....	5-16
Figure 5.10	Dissolved BTEX Concentrations in Shallow Groundwater Phase II - August/September 1995 .....	5-18
Figure 5.11	Dissolved Benzene Concentrations in Shallow Groundwater Phase II - August/September 1995 .....	5-19
Figure 5.12	Dissolved 1,2,4-TMB and 1,3,5-TMB Concentrations in Shallow Groundwater Phase II - August/September 1995 .....	5-21
Figure 5.13	Dissolved Naphthalene Concentrations in Shallow Groundwater Phase II - August/September 1995 .....	5-22
Figure 5.14	Detected Benzene Concentrations in Surface Water and Sediment 1995 .....	5-24
Figure 6.1	Historical Variation in Dissolved BTEX Concentrations (Wells/Points MW-02, MW-03, MOC-08, and MOC-11) .....	6-8
Figure 6.2	Historical Variation in Dissolved BTEX Concentrations (Wells/Points MW-112, MW-113, MOC-04, and MOC-05) .....	6-9
Figure 6.3	Sequence of Microbially Mediated Redox Processes .....	6-14

## TABLE OF CONTENTS (Continued)

### LIST OF FIGURES (Continued)

<u>No.</u>	<u>Title</u>	<u>Page</u>
Figure 6.4	Oxidation-Reduction Potentials (ORP) in Shallow Groundwater Phase II - August/September 1995 .....	6-16
Figure 6.5	Extent of Oxidized Electron Acceptors .....	6-17
Figure 6.6	Extent of Byproducts of Electron Acceptor Reduction .....	6-20
Figure 6.7	Soil Benzene Leaching Rate Based on Batch Flushing Model .....	6-32
Figure 6.8	Simulated Maximum Benzene Concentrations at Drainage Ditch - Natural Attenuation Only .....	6-35
Figure 6.9	Predicted Extent of Dissolved Benzene, Natural Attenuation Only .....	6-36
Figure 7.1	Final Conceptual Site Model .....	7-5
Figure 9.1	Biosparging System Layout with 1995 Dissolved Benzene Concentrations .....	9-6
Figure 9.2	Groundwater Extraction and SVE System Layout with 1995 Benzene Concentrations .....	9-8
Figure 9.3	Predicted Impact of Biosparging on Dissolved Benzene Plume Over Time.....	9-12
Figure 9.4	Predicted Impact of Natural Attenuation only on Dissolved Benzene Plume Over Time .....	9-13
Figure 9.5	Simulated Maximum Benzene Concentrations at Drainage Ditch Over Time .....	9-14
Figure 10.1	Biosparging System Layout, MPs, LTM Wells, and Surface Water Sampling Locations.....	10-3
Figure 10.2	Conceptual Biosparging System .....	10-4
Figure 10.3	Corrective Action Schedule .....	10-9

## LIST OF ACRONYMS AND ABBREVIATIONS

AFB	Air Force Base
AFBCA	Air Force Base Conversion Agency
AFCEE	Air Force Center for Environmental Excellence
AS	Air Sparging
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, xylenes
°C	degrees Celsius
CAP	corrective action plan
cfm	cubic feet per minute
cm/sec	centimeters per second
CO <sub>2</sub>	carbon dioxide
COC	chemical of concern
COPC	chemical of potential concern
CPT	cone penetrometer testing
CSM	conceptual site model
CT	central tendency
DAF	dilution/attenuation factor
DO	dissolved oxygen
EA	environmental assessment
EDB	ethylene dibromide
Eh	reduction/oxidation potential
ERM	Environmental Resources Management, Inc.
ES	Engineering-Science, Inc.
ET	evapotranspiration
°F	degrees Fahrenheit
FID	flame ionization detector
ft/day	feet per day
ft/ft	foot per foot
f <sub>oc</sub>	fractional organic carbon content
GAC	granular activated carbon
GC	gas chromatograph(y)
gpm	gallons per minute
HDPE	high-density polyethylene
ICE	internal combustion engine
ID	inside diameter
IRIS	Integrated Risk Information System
IRP	Installation Restoration Program
IWWTP	industrial wastewater treatment plant
K <sub>d</sub>	distribution partition coefficient
kg	kilogram

Laidlaw	Laidlaw Environmental Services, Inc.
Law	Law Environmental Services, Inc.
LEL	lower explosive limit
LIF	laser induced fluorescence
LNAPL	light nonaqueous-phase liquid
LTM	long-term monitoring
LTMP	long-term monitoring plan
MCL	maximum contaminant level
MDL	method detection limit
mg	milligram
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
mg/m <sup>3</sup>	milligrams per cubic meter
mL	milliliter
mm Hg	millimeter of mercury
MOGAS	motor gasoline
msl	mean sea level
MTBE	methyl tert butyl ether
mV	millivolts
µg/kg	microgram per kilogram
µg/L	microgram per liter
µmhos/cm	micromhos per centimeter
NPDES	National Pollutants Discharge Elimination System
NRMRL	National Risk Management Research Laboratory
O <sub>2</sub>	oxygen
OD	outside diameter
O&M	operation and maintenance
ORP	oxidation/reduction potential
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
PAH	polycyclic aromatic hydrocarbon
Parsons ES	Parsons Engineering Science, Inc.
PEL	permissible exposure limit
PID	photoionization detector
POC	point of compliance
POL	petroleum, oils, and lubricants
ppmv	parts per million, volume per volume
PQL	practical quantitation limit
PRL	project reporting limit
PVC	polyvinyl chloride
QA	quality assurance
QAPP	quality assurance project plan
QC	quality control
RBCA	risk-based corrective action
RBSL	risk-based screening level

QC	quality control
RBCA	risk-based corrective action
RBSL	risk-based screening level
redox	reduction/oxidation
RME	reasonable maximum exposure
SAP	sampling and analysis plan
SCDHEC	South Carolina Department of Health and Environmental Control
scfm	standard cubic feet per minute
SDWA	Safe Drinking Water Act
SESOIL	seasonal soil compartment model
SSTL	site-specific target level
SVE	soil vapor extraction
SVOC	semivolatile organic compound
Target	Target Environmental Services, Inc.
TDS	total dissolved solids
TEMB	tetramethylbenzene
TIC	total inorganic carbon
TMB	trimethylbenzene
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TVH	total volatile hydrocarbons
TWA	time-weighted-average
US	United States
USEPA	US Environmental Protection Agency
USGS	US Geological Survey
UST	underground storage tank
UV	ultraviolet
VOC	volatile organic compound
WQC	water quality criteria
WWTP	wastewater treatment plant
YSI	Yellow Springs Instruments

## SECTION 1

### INTRODUCTION

#### 1.1 PURPOSE AND SCOPE

Parsons Engineering Science, Inc. (Parsons ES), [formerly Engineering-Science, Inc. (ES)] was retained by the United States (US) Air Force Center For Environmental Excellence (AFCEE) to prepare a corrective action plan (CAP) in support of a risk-based corrective action (RBCA) decision for soil and groundwater contaminated with fuel hydrocarbons at the Motor Gasoline (MOGAS) Storage Area, hereafter referred to as the MOGAS site, located at the former Myrtle Beach Air Force Base (AFB), Myrtle Beach, South Carolina. The site, located at the former Motor Pool adjacent to Building 514, is also referred to as Installation Restoration Program (IRP) Site SS-20. Soil and groundwater at the MOGAS site have been impacted by petroleum hydrocarbons released from one or more leaking fuel underground storage tanks (USTs).

RBCAs are designed to combine natural physical, chemical, and biological remediation processes with low-cost source reduction technologies, such as *in situ* bioventing, as necessary, to economically reduce potential risks to human health and the environment posed by subsurface petroleum hydrocarbon fuel spills. This CAP has been prepared as part of a multi-site initiative sponsored by AFCEE to develop a standard remediation handbook that describes a process of using natural attenuation, low-cost technologies, and focused risk assessments to obtain site closure. The MOGAS site is one of several sites nationwide that will be used as a case study in the development of this handbook.

The original goal of this CAP was to provide the technical documentation necessary for the Base to obtain site closure under the "mixing zone" rule of the South Carolina Water Classifications and Standards (R.61-68 and R.61-69) [South Carolina Department of Health and Environmental Control (SCDHEC), 1994]. The mixing zone rule allows less stringent, alternative maximum contaminant levels (MCLs) to be applied as cleanup goals at a contaminated site if it can be demonstrated that : 1) the contaminant source has been removed, remediated, and/or contained; 2) the remaining groundwater contamination will not significantly impact surface water quality or sensitive receptors; 3) the contamination is contained within the property boundary of its source; and 4) the contaminant concentrations, either singularly or in combination, are not dangerously toxic, mobile, or persistent. Since the project work plan (Parsons ES, 1994) was developed, state guidance for a tiered RBCA analysis of petroleum release sites has been issued by SCDHEC (1995). Therefore, this more recent guidance was used to prepare this CAP, and the work plan was modified as necessary to comply with the most current SCDHEC guidance. If desired, the results of the

RBCA analysis can be used to support a groundwater mixing zone variance for the MOGAS site, as appropriate.

The SCDHEC (1995) guidance is based on the American Society for Testing and Materials (ASTM, 1995) *Standard Guide for Risk-Based Corrective Action at Petroleum Release Sites* (ASTM E1739-95). This standard provides a tiered approach to establish site-specific corrective action requirements based on an evaluation of potential receptor exposures to chemical contamination at or migrating from a petroleum hydrocarbon release site. SCDHEC (1995) requires releases to be classified with respect to the timeframe in which potential receptors could be exposed to site-related contamination. Prioritization is an ongoing process based on available information, such as extent of contamination, contaminant fate and transport estimates, and effectiveness of any interim corrective actions.

Once a release site has been initially classified, a Tier 1 evaluation is performed. A Tier 1 evaluation is a screening-level assessment wherein contaminant concentrations measured in site media are compared to generic screening criteria that are based on conservative exposure factors, potential receptor exposure pathways, and land use. Based on this comparison, more site-specific risk evaluations and appropriate corrective actions can be identified. Tier 1 risk-based screening levels (RBSLs) have been defined for both unrestricted (i.e., residential) and industrial/commercial land use assumptions by SCDHEC (1995). In the event that measured site concentrations exceed the applicable Tier 1 RBSLs, and remediation to Tier 1 RBSLs is not practicable, either an interim corrective action or a Tier 2 evaluation may be pursued. If an interim corrective action is deemed not necessary, a Tier 2 evaluation is conducted to establish reasonable, risk-based target cleanup objectives for a specific site. A Tier 2 evaluation is more comprehensive than a Tier 1 analysis because it requires more quantitative contaminant fate and transport calculations and the development of site-specific remediation goals for potential exposure pathways based on reasonable exposure assumptions and actual land use considerations. Tier 2 site-specific target levels (SSTLs) are based on the outcome of a predictive exposure pathways analysis conducted to evaluate current and potential future human health risks and the short- and long-term fate of the contaminants at the site. Although Tier 2 evaluations usually involve more rigorous analysis and may require use of institutional controls to ensure that exposure conditions do not change over time, they should result in a more focused remediation of contaminants that may actually pose a risk to potential receptors (SCDHEC, 1995).

This CAP documents the reasonable potential risks to human health and the environment (i.e., nonhuman "ecological" receptors) due to exposure to chemical contaminants originating from the MOGAS site under current conditions. The CAP also estimates the potential risks to human and ecological receptors due to exposure to chemical contaminants over time, accounting for the effects of natural chemical attenuation processes. Finally, the CAP develops and describes a recommended remedial approach for fuel hydrocarbon contamination in soils, and groundwater at and downgradient from the MOGAS site that can achieve the Tier 2 SSTLs. This CAP is being submitted for review and approval in accordance with SCDHEC (1995) program requirements.

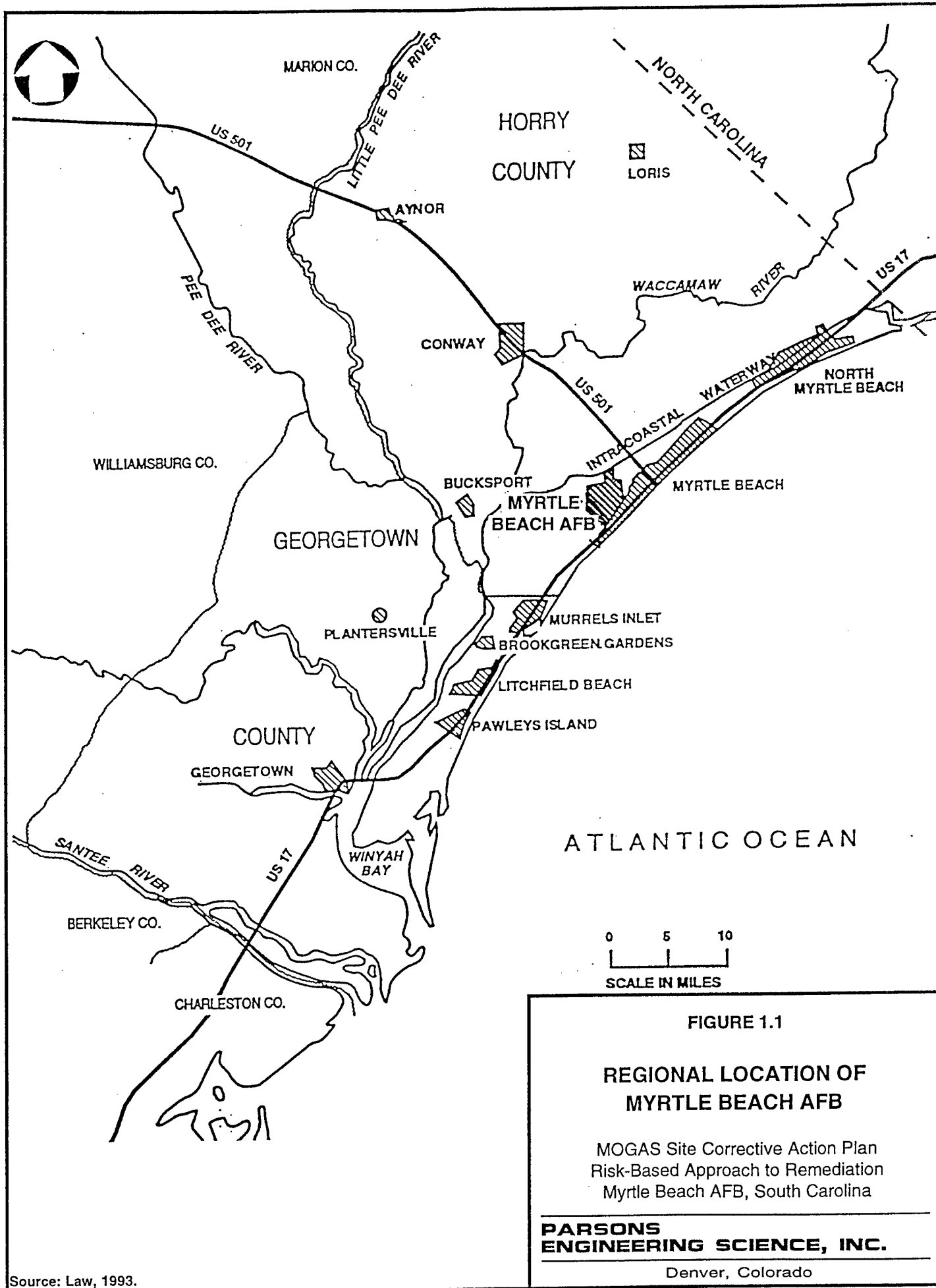
## 1.2 REPORT ORGANIZATION

This CAP is presented in two volumes and consists of 11 sections, including this introduction, and 10 appendices. Site background, including operational history and a review of environmental site investigations conducted to date, are provided in the remainder of this section. Section 2 summarizes the 1995 site characterization activities performed by Parsons ES. Physical characteristics of the MOGAS site and surrounding environs are described in Section 3. A Tier 1 evaluation is completed in Section 4 to identify those site-related contaminants that are considered chemicals of potential concern (COPCs). Section 5 summarizes the nature and extent of COPC contamination at the site. Section 6 addresses the effects of natural chemical attenuation processes that are documented to be occurring at the site, and presents quantitative fate and transport and exposure pathways analyses. The comprehensive Tier 2 evaluation, including the development of SSTLs, is detailed in Section 7. Section 8 presents contaminant treatability pilot test results for soil vapor extraction (SVE), and evaluates this low-cost source reduction technology. Section 9 presents a comparative analysis of three candidate remedial alternatives. Section 10 is a more detailed implementation plan for the recommended remedial alternative, and includes a detailed long-term monitoring (LTM) plan. Section 11 presents references used in preparing this CAP. Sections 1 through 11 are presented in Volume I of this CAP.

Appendix A presents pertinent figures and tables produced during previous investigations [Environmental Resources Management (ERM), 1990; Law Environmental Services, Inc. (Law), 1993 and 1994] that show sampling locations and investigation results. Appendix B presents soil gas, soil, and groundwater analytical results from the 1995 sampling events conducted by Parsons ES, and from the Parsons ES 1995-1996 SVE pilot test. Appendix C contains borehole logs, well construction diagrams, well development data, and water level measurements for all sampling activities completed by Parsons ES at the MOGAS site. Aquifer test data and analyses are presented in Appendix D. Appendix E presents the algorithms used to derive Tier 1 RBSLs. Appendix F includes the quantitative calculations and fate and transport model results used in the predictive chemical fate assessment. Appendix G presents the derivation of Tier 2 SSTLs. Appendix H presents the source reduction treatability test results, and Appendix I summarizes the screening and development of remedial alternatives considered in detail within this CAP. Appendix J presents a site-specific sampling and analysis plan (SAP) for use during long-term monitoring at the site. The 10 appendices to this CAP are included in Volume II.

## 1.3 MOGAS SITE DESCRIPTION AND OPERATIONAL HISTORY

Myrtle Beach AFB is located in Horry County, South Carolina, along the Atlantic Ocean coast. The Base is located about 4 miles southwest of downtown Myrtle Beach, South Carolina, and occupies an area of approximately 3,793 acres on a strip of land known as the Grand Strand. Myrtle Beach AFB is bordered by the city of Myrtle Beach on the east and south, the Intracoastal Waterway on the north, and wetlands, timberland, and undeveloped land on the west (Figure 1.1) (ES, 1981). The runways and the eastern side of the Base have been converted for use as the Myrtle Beach Municipal Jetport. These facilities also served as a municipal airport prior to 1940 and from 1947 to 1954. The Army Air Corps incorporated the airport into the national defense program from 1940 to 1947. In 1954, the airport was donated to the Air



Source: Law, 1993.

Force. Myrtle Beach AFB was host to the 354th Tactical Fighter Wing under the direction of the Tactical Air Command prior to closure in March 1993. The Base is currently undergoing closure under the direction of the Air Force Base Conversion Agency (AFBCA).

The MOGAS site is located in the northwestern quadrant of the Base, west of Shine Avenue, east of Third Street, and north of Phylliss Drive (Figure 1.2). The MOGAS site was the location of the former motor pool, which provided fueling and repair services for motor vehicles on the Base. A westerly-flowing, unlined, man-made drainage ditch is present along the southern edge of the MOGAS site, north of Phylliss Drive (Figure 1.2). A shallow, intermittent, southerly-flowing drainage ditch is present along the eastern boundary of the site. The MOGAS site is relatively flat, with elevations ranging from about 25 feet above mean sea level (msl) in the central portion of the site to approximately 15 feet msl along the man-made drainage ditch that borders the site to the south. The MOGAS site is approximately 425 feet by 550 feet in area, paved with asphalt, and completely surrounded by a 6-foot-high chain-link fence. Figure 1.3 shows the MOGAS site in relation to other fuel storage areas in the vicinity.

Four 5,000-gallon USTs located at the MOGAS site were used to store gasoline and diesel fuel for motor pool operations. Three of the tanks were used for gasoline storage, and one tank was used for diesel fuel storage (ES, 1981). The USTs were previously situated in pairs at two locations south of Building 514 (Figure 1.4). The former tank locations are referred to as the eastern and western UST locations in this report. Information presented by Law (1994) indicates that the tanks were approximately 4 feet in diameter, and that the bottoms of the tanks were at a depth of approximately 10 feet below ground surface (bgs).

In 1983, Base personnel observed a fuel sheen on water in the southern drainage ditch and stressed vegetation on the northern bank of the ditch. As a result of these observations, Base personnel installed two corrugated steel observation wells at the site (Figure 1.4). During installation of these wells, subsurface soils were found to be saturated with fuel. Floating product also was observed on the groundwater surface. The leaking UST was subsequently drained and abandoned (Law, 1993). In 1985 and 1987, two of the three remaining tanks were removed from service due to suspected leaks indicated by routine product level measurements. The available historical information does not indicate which tank was found to be leaking. However, the locations of the observation wells installed by the Air Force indicate that it was at the western UST location.

The Base was closed in March 1993, and in April 1993 Laidlaw Environmental Services (Laidlaw) excavated and removed the four USTs and associated delivery lines, backfilled the excavations with clean soils, and repaved the excavation areas with asphalt. Groundwater was not encountered at the site during tank excavation activities.

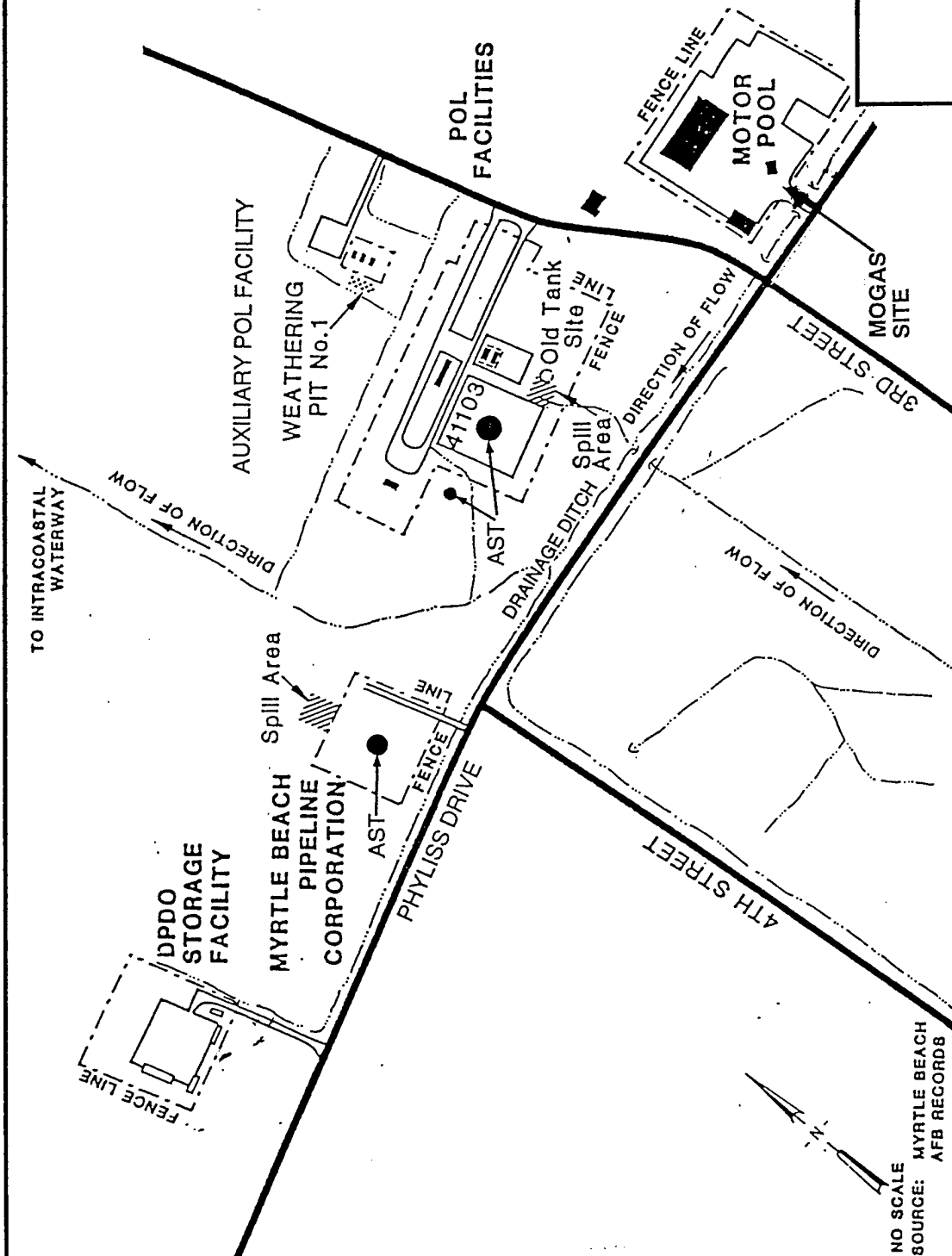


FIGURE 1.3

# PROXIMITY OF OTHER FUEL STORAGE AREAS TO THE MOGAS SITE

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**

Denver, Colorado

During excavation, large quantities of contaminated soil were encountered. Because of the large volume and areal extent of contaminated soils present in the excavation, the majority of the gasoline-contaminated soils were left in place (Law, 1993).

#### **1.4 RESULTS OF PREVIOUS REMEDIAL INVESTIGATIONS**

The MOGAS site has been included in several Base investigations since its identification as a potentially contaminated site. The initial remedial investigation at this site was conducted under the IRP in 1988 by ERM (1990). This investigation provided an initial understanding of the site hydrogeology and the nature and extent of contamination. Soil boreholes, monitoring wells, and soil, soil gas, groundwater, and surface water sampling and analysis were included in the investigation. A more comprehensive investigation was subsequently conducted by Law (1993 and 1994). This investigation was completed to support development of a draft CAP for the MOGAS site (Law, 1994) and included further delineation of the extent of benzene, toluene, ethylbenzene, and xylene (BTEX) contamination at the site. Investigation tasks conducted by Law or their subcontractor, Target Environmental Services, Inc. (Target), included a soil gas survey; groundwater quality screening; soil borehole drilling; monitoring well installation; sampling and analysis of soil, groundwater, surface water, and drainage ditch sediment; and aquifer testing.

The results of previous site investigations are presented in the following reports:

- IRP Long Term Monitoring, Stage I Remedial Investigation (ERM, 1990);
- IRP Draft Stage 2 Remedial Investigation (Law, 1993);
- Soil Gas and Groundwater Survey (Target, 1993); and
- IRP Draft Corrective Action Plan for the MOGAS Site (Law, 1994).

All available site-specific data from these sources, and subsequent data collected by Parsons ES in 1995, are used in this CAP to characterize the nature and extent of COPCs, and to determine the type, magnitude, and timing of remediation necessary to protect human health and the environment. The following paragraphs summarize the site characterization data prior to the Parsons ES 1995 investigation. Pertinent figures and tables produced during prior investigations are contained in Appendix A.

##### **1.4.1 Soil Gas**

Soil gas investigations have identified elevated concentrations of total volatile organic compounds (VOCs) in the area of the former USTs and along the narrow, sloping, grassy strip between the former USTs and the drainage ditch. Twenty-six soil gas points were installed, sampled, and analyzed in the field using a photoionization detector (PID) by ERM (1990) in 1988 (see Appendix A for sampling locations). This soil gas screening indicated elevated VOC concentrations ranging between 0 and 134 parts per million, volume per volume (ppmv). The highest soil gas VOC concentrations were measured near the former UST locations and along the northern bank of the southern drainage ditch near monitoring well MW-112 (Figure 1.4) (ERM, 1990).

A subsequent soil gas survey was conducted by Target (1993) in June 1993 to determine the lateral extent of fuel-related hydrocarbons in the shallow subsurface soils. Sixty-three soil gas samples were collected and analyzed for petroleum hydrocarbons using a field gas chromatograph (GC) equipped with a flame ionization detector (FID). Elevated concentrations of total VOCs were found in soil gas samples over the general areas of the former USTs. GC/FID signatures of the soil gas samples were characteristic of relatively unweathered gasoline. The highest concentration of soil gas VOCs generally occurred in the areas immediately adjacent to and downgradient from the former UST locations, where the soil gas VOC concentrations exceeded 100,000 micrograms per liter ( $\mu\text{g/L}$ ) (420,000 ppmv). A single soil gas sample located near the northwest corner of Building 507 (Figure 1.4) also exhibited VOC concentrations exceeding 420,000 ppmv (Target, 1993).

#### 1.4.2 Soils

ERM (1990) drilled five soil boreholes to a depth of 11 feet bgs in November 1988. Three of these boreholes were completed as groundwater monitoring wells MW-111, MW-112, and MW-113 (Figure 1.4). Selected soil samples were analyzed for VOCs (including BTEX), semivolatile organic compounds (SVOCs), total petroleum hydrocarbons (TPH), total lead, and total chromium. Analytical results indicated the presence of BTEX, polynuclear aromatic hydrocarbons (PAHs), and TPH at concentrations exceeding the analytical detection limits. Soil samples from borehole B-216 and monitoring well MW-112 (Figure 1.4 and Appendix A) exhibited the highest concentrations of the detected constituents. These sampling locations are situated downgradient from the western UST location. Total BTEX concentrations of 1,554 milligrams per kilogram (mg/kg) and 53.7 mg/kg were reported at MW-112 and B-216, respectively. PAH compounds also were detected in composite soil cuttings samples from borehole B-216 and well MW-112; however, most of the concentrations were estimated values (assigned a "J" qualifier) based on quality control (QC) data. Unqualified PAH detections included naphthalene (5.1 mg/kg), benzo(b)fluoranthene (0.085 mg/kg), and 2-methylnaphthalene (8.5 mg/kg). These compounds were detected in soil samples from well MW-112 (ERM, 1990).

In April 1993, Laidlaw excavated and removed the four USTs from the site. Soil samples for BTEX and TPH analysis were collected from soils left in place in the excavations. Reported BTEX concentrations ranged from below the detection limit ( $< 1$  mg/kg) to 79.9 mg/kg. TPH concentrations ranged from 6 mg/kg to 2,800 mg/kg. These analytical results were reported by Law (1993).

Law (1994) drilled 31 soil boreholes in 1994 at the MOGAS site to further assess the extent of BTEX contamination in subsurface soils (Figure 1.4). The soil borehole locations were selected using the soil gas (Section 1.3.2.1) and groundwater (Section 1.3.2.3) screening results and data available from the UST excavation and removal. Two soil samples were selected from each borehole for laboratory analysis based on the results of PID field screening. Benzene concentrations in the soil ranged from not detect to 63 mg/kg. Total BTEX concentrations ranged from not detected to 912 mg/kg. The highest benzene and BTEX concentrations were detected in soil samples collected near the former eastern UST location at depths between 6 and 10 feet bgs. The distribution of BTEX in soils is similar to the distribution of BTEX in soil gas measured in June 1993 (Target, 1993; Law, 1994). The distribution of gasoline-range

TPH concentrations detected at the site is similar to that of BTEX concentrations, and ranged from below the detection limit to 39,000 mg/kg. The highest TPH concentrations detected were from soil samples collected near the eastern former UST location at a depth of 8 to 10 feet bgs.

#### 1.4.3 Groundwater

Three of the soil boreholes drilled by ERM (1990) in 1988 were completed as monitoring wells (MW-111, MW-112, and MW-113). Groundwater samples were collected for laboratory analysis from these wells in December 1988. The highest groundwater contaminant concentrations were detected at well MW-112 (Figure 1.4), where a total BTEX concentration of 33,500 µg/L was measured. 1,4-Dichlorobenzene also was detected in a groundwater sample from well MW-112 at a concentration of 5,100 µg/L. Benzene and total lead were detected in groundwater from well MW-113 at concentrations of 15 µg/L and 0.025 milligrams per liter (mg/L), respectively. No VOCs were detected in monitoring well MW-111 (ERM, 1990).

A groundwater screening survey was conducted by Target in June 1993, under contract to Law, to evaluate groundwater quality in the areas exhibiting the highest soil gas VOC concentrations. Ten samples were collected from temporary groundwater sampling points and analyzed in the field using a GC/FID. Three samples were collected for fixed-base laboratory analysis to verify field results. BTEX constituents were detected in all of the samples analyzed. Groundwater samples collected downgradient from the former UST locations exhibited total BTEX concentrations between 45 and 1,920 µg/L. The highest BTEX concentration was found downgradient from the eastern UST location (Target, 1993).

Five additional monitoring wells (MW-01 through MW-05) were installed by Law (1994) in March 1994 to further define the extent of BTEX contamination in the shallow groundwater beneath the MOGAS site (Figure 1.4). Eight groundwater samples were collected in April 1994 from these wells and the three wells previously installed at the site to determine the distribution of BTEX and total lead in shallow groundwater at the site. Total BTEX concentrations ranged from not detected (< 1 µg/L) to 64,300 µg/L. BTEX compounds were not detected in upgradient wells MW-111 and MW-01 or in downgradient well MW-03. Wells MW-112 and MW-113, located downgradient from the former UST locations along the northern bank of the southern drainage ditch, exhibited the highest BTEX concentrations of 64,300 and 12,010 µg/L, respectively. Total lead concentrations were similar in all of the wells, and ranged from not detected (< 1 µg/L) to 5.7 µg/L (Law, 1994).

#### 1.4.4 Free Product

Measurable free-phase product, or mobile light nonaqueous-phase liquid (LNAPL) fuel, has not been frequently observed at the MOGAS site and generally has only occurred in the area of monitoring well MW-112. Mobile LNAPL was previously identified by Base personnel in collection wells installed downgradient from the western UST location in 1983 (ERM, 1990). These wells were used to collect an unknown quantity of free product. Monitoring well MW-112 was subsequently installed near these wells in 1988. During the ERM investigation, a mobile LNAPL layer was observed in well MW-112, but the thickness was not reported. Mobile LNAPL was

not reported in any well during the Law (1993 and 1994) investigations. However, an oily sheen was reported on groundwater seeping into the drainage ditch immediately downgradient from MW-112 (ERM, 1990), and Law (1994) reported the presence of a sheen on the water surface in the ditch.

#### 1.4.5 Surface Water

Fuel sheens have been observed on surface water in the southern drainage ditch located approximately 100 feet hydraulically downgradient from the former USTs. The sheens have been observed only in the areas near monitoring wells MW-112 and MW-113. Two surface water samples (SW-5 and SW-6) were collected by ERM (1990) from the drainage ditch. Sample SW-5, located upstream from monitoring well MW-113 (Figure 1.4), exhibited a total lead concentration of 0.0099 mg/L. No VOCs were detected. Total lead and benzene were detected in sample SW-6, downstream from MW-112, at concentrations of 0.0125 mg/L and 2 µg/L, respectively. Concentrations of TPH in samples SW-5 and SW-6 were 11 and 23 mg/L, respectively.

Four surface water samples were collected from the drainage ditch in March 1994. Total BTEX concentrations in the surface water samples ranged from not detected (< 1 µg/L) to 50.6 µg/L. The highest BTEX concentrations occurred in samples SW-03 (50.6 µg/L) and SW-04 (43.3 µg/L), which are located near well MW-112 (Figure 1.4). The concentrations of benzene were similar, ranging between 14 and 16 µg/L in all samples except the upstream (background) location, where benzene was not detected (< 0.5 µg/L). Total lead concentrations in these surface water samples ranged between 1.4 and 2.8 µg/L (Law, 1994).

#### 1.4.6 Stream Sediment

Eight sediment samples were collected from the bottom of the ditch in March 1994 (Figure 1.4). Total BTEX concentrations ranged from below the detection limit [< 1 microgram per kilogram (µg/kg)] to 140,000 µg/kg. Sample SD-06, located just downstream from surface water sampling location SW-03 and well MW-113 (Figure 1.4), exhibited the highest concentration of total BTEX. Total lead concentrations in the sediment samples ranged between 6.2 and 75 mg/kg. Sediment samples SD-07 and SD-08 contained the highest concentrations of total lead. These samples were from locations farthest downstream from the site, and exhibited total lead concentrations of about 10 times those detected in the upstream (i.e., background) samples (Law, 1994).

## SECTION 2

### SITE CHARACTERIZATION ACTIVITIES

Since 1988, several site characterization investigations have been conducted at the MOGAS site by various Air Force contractors. These earlier investigations focused on characterizing and delineating the areal extent of fuel hydrocarbon contamination in soil gas, soil, groundwater, surface water, and sediments, and to a lesser degree, on determining the vertical extent of fuel hydrocarbons at the site. Parsons ES conducted three separate field investigations at the MOGAS site between January 1995 and January 1996 that consisted of initial site characterization screening activities (Phase I), supplemental site characterization sampling activities (Phase II), and source reduction pilot testing (Phase III). These tasks were conducted to more completely define the vertical and horizontal extent of fuel hydrocarbons in soils and groundwater; to determine the impacts of groundwater discharge on surface water and sediments in the drainage ditch that forms the southern site boundary (Figure 1.4); to collect site-specific data to quantify the effects of natural contaminant attenuation processes; and to test low-cost source reduction technologies to facilitate risk-based corrective action (RBCA) decisions and remedial systems design. Data gaps identified from previous investigations were addressed by Parsons ES as part of this RBCA investigation.

To support and implement a RBCA at the MOGAS site, additional data were collected by Parsons ES to: (1) establish groundwater flow characteristics, groundwater and soil geochemistry, and aquifer parameters; (2) evaluate the potential for contaminant source areas to further degrade groundwater quality; (3) identify the impact of groundwater discharge on surface water and sediment quality; and (4) identify potential contaminant receptors and receptor exposure points. Sufficient data were collected to conduct a quantitative fate and transport analysis, to perform an exposure pathways analysis, and to evaluate the potential treatability of contaminated media using low-cost remediation technologies. To the extent practicable, data previously collected by other contractors were used to augment this study and to facilitate the field investigation. In filling the data gaps from previous investigations, emphasis was placed on characterizing the nature and extent of source area soil contamination and groundwater and surface water quality, and on collecting data documenting natural attenuation (specifically biodegradation) of fuel hydrocarbons in soils, groundwater, surface water, and drainage ditch sediments at the site.

#### 2.1 SCOPE OF DATA COLLECTION ACTIVITIES

The chemicals initially targeted for study at this site were identified from the results of previous investigations and the chemical composition of the primary contaminant source (MOGAS fuel). MOGAS released from the former UST(s) is considered the

primary contaminant source that has impacted soil, groundwater, surface water, and sediment. Major hydrocarbon constituents in MOGAS (and their percentages by weight) are: n-alkanes (15 to 17 percent), branched alkanes (28 to 36 percent), cycloalkanes (3 to 5 percent), benzenes and alkylbenzenes (20 to 49 percent), naphthalenes (1 percent or less), and olefins (1 to 11 percent) (Arthur D. Little, 1987).

The fuel-derived chemicals identified and addressed as part of this study include the BTEX compounds, trimethylbenzene (TMB) isomers, tetramethylbenzene (TEMB) isomers, naphthalene, and chlorobenzene. These compounds were targeted based on the environmental fate of various hydrocarbons, previous site assessment results, and SCDHEC (1995) regulatory analytical requirements for petroleum UST sites. Additionally, analyses were performed for an extended list of PAHs and other SVOC compounds to determine if any diesel fuel releases may have occurred at the site. USEPA NRMRL in Ada, Oklahoma; Evergreen Analytical, Inc. in Wheat Ridge, Colorado, and Air Toxics, Limited (Ltd.) in Folsom, California, provided fixed-base quantitative laboratory analyses of selected samples. Field analyses and measurements also were performed for various geochemical and physical parameters to document natural biodegradation processes and to assess the potential effectiveness of low-cost source reduction technologies.

The RBCA investigation of the MOGAS site was conducted according to the methods presented in the final draft work plan (Parsons ES, 1994). As described in Section 1.1, the work plan was originally developed according to available guidelines and requirements to support an application for a mixing zone variance for groundwater in South Carolina (SCDHEC, 1994). More recent state guidance for a tiered RBCA analysis of petroleum release sites (SCDHEC, 1995) was used to prepared this CAP, and the work plan was modified as necessary to comply with this more recent guidance. The RBCA process provides the necessary framework to support the acquisition of a mixing zone variance for groundwater.

As previously mentioned, the RBCA investigation was conducted in phases. Sampling and testing activities performed by Parsons ES during each phase are summarized below.

#### **Phase I - Initial Site Characterization Screening**

- Cone penetrometer testing (CPT) pushes at 21 locations (CPT1 through CPT21) to quantify subsurface lithology and contamination.
- Installation of 14 groundwater monitoring points ( MOC-02, MOC-03, MOC-04, MOC-05, MOC-07, MOC-08, MOC-10, MOC-11, MOC-12, MOC-13, MOC-19, MOC-20, MOC-21, and MOV-01-03) and 4 soil vapor monitoring points (SV-01 through SV-04).
- Collection of 16 groundwater samples from 8 of the newly-installed groundwater monitoring points (MOC-02, MOC-03, MOC-04, MOC-05, MOC-07, MOC-08, MOC-11, and MOV-01-03) and eight previously installed monitoring wells (MW-01 through MW-05 and MW-111 through MW-113).

## **Phase II - Supplemental Site Characterization Sampling**

- Installation of 14 additional groundwater monitoring wells (MW-06 through MW-19), including 5 paired well clusters; 2 air sparging (AS) wells (AS-01 and AS-02); 4 additional vapor monitoring points (SV-05 through SV-08); and 2 SVE wells (VENT-01 and VENT-02).
- Collection of 42 subsurface soil samples for laboratory analysis from 14 of the boreholes drilled for the installation of new monitoring wells, AS wells, and SVE wells.
- Collection of 37 groundwater samples from a total of 37 groundwater monitoring wells or monitoring points, including 21 monitoring wells or monitoring points previously installed during Phase I, the 14 new monitoring wells, and 2 AS wells.
- Field and fixed-base laboratory analysis of the 37 groundwater samples for a suite of inorganic and geochemical parameters and VOCs. Eleven selected groundwater samples also were analyzed for SVOCs.
- Performance of aquifer slug tests on seven wells to estimate the hydraulic conductivity of the surficial (water table) aquifer.
- Establishment of four permanent surface water monitoring stations.
- Collection of four surface water (SW-01 through SW-04) and four sediment (SD-01 through SD-04) samples at the permanent surface water monitoring stations for field and fixed-base laboratory analysis.
- Measurement of surface water flow velocities using a Pygmy™ surface water flow meter.
- Measurement of groundwater and surface water levels at all of the site monitoring wells, temporary monitoring points, and permanent surface water monitoring stations.
- Surveying the horizontal and vertical locations of all of the monitoring wells, temporary groundwater sampling locations, and vapor monitoring points at the MOGAS site, including the previously existing monitoring wells, to a common elevation and coordinate system.

## **Phase III - Source Reduction Pilot Testing**

- Collection of four soil gas samples for quantitative laboratory analysis from two vapor monitoring points (SV-02 and SV-07) and the two SVE wells (VENT-01 and VENT-02).
- Measurement of soil gas parameters using portable field instruments for oxygen (O<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), and total volatile (gasoline-range) hydrocarbons

(TVH) from the eight vapor monitoring points (SV-01 through SV-08) and the two SVE wells (VENT-01 and VENT-02).

- Performance of a 3-month-long SVE pilot test using SVE wells VENT-01 and VENT-02. Extracted soil gases were treated using an internal combustion engine (ICE) and ULTROX™ ultraviolet (UV) oxidation off-gas treatment technologies.

Analytical detection limit requirements were considered before site characterization work was initiated, and suitable analytical methods and QC procedures were selected to ensure that the data collected under this program are of sufficient quality to be used in a quantitative risk assessment (Parsons ES, 1994).

Table 2.1 summarizes the analytical methods used for the Phase I, Phase II, and Phase III environmental samples, respectively. This table also lists the laboratory-specified method detection limits (MDLs) and practical quantitation limits (PQLs) for each analytical method by analyte and sample matrix. The MDL is the lowest concentration at which a particular chemical can be measured and distinguished with 99-percent confidence from the normal "noise" of an analytical instrument or method. The PQL is the lowest level at which a chemical can be accurately and reproducibly quantitated. A portion of the analyses performed during each investigative phase were conducted in the field. The Phase I fixed-base laboratory analyses were performed at the USEPA NRMRL in Ada, Oklahoma. Phases II and III fixed-base analyses were performed at Evergreen Analytical, Inc. in Wheat Ridge, Colorado, and Air Toxics, Ltd. in Folsom, California, respectively. The field and fixed-base laboratory analyses conducted for each location sampled by Parsons ES during the RBCA investigations are summarized in Tables 2.2 (Phase I), 2.3 (Phase II), and 2.4 (Phase III). Field sampling and testing activities performed during each phase are summarized in the following sections.

## **2.2 PHASE I - INITIAL SITE CHARACTERIZATION SCREENING**

Phase I site characterization field activities were conducted by Parsons ES in January 1995. These activities involved CPT to confirm subsurface lithology and contaminant conditions, and installation of groundwater and soil vapor monitoring points at some of the CPT locations. One groundwater monitoring point (MOV-01-03) was hand-driven. Groundwater samples for screening analyses were collected at the groundwater monitoring points.

### **2.2.1 Cone Penetrometer Testing and Monitoring Point Installation**

Initial site characterization field activities were conducted by Parsons ES in January 1995. Subsurface conditions at the site were initially characterized during Phase I using CPT coupled with laser-induced fluorescence (LIF). CPT pushes were performed at 21 locations (CPT-1 through CPT-21) to characterize subsurface stratigraphy using a piezocone. LIF was performed simultaneously at all these locations, except CPT-14 and CPT-19 through CPT-21 (LIF damaged), to evaluate the extent of residual or mobile hydrocarbons in the soils. The CPT push locations that were completed as either groundwater or soil vapor monitoring points were

**TABLE 2.1**  
**ANALYTE REPORTING LIMITS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Analyte	Analytical Method	Field or Fixed-Base	Soil Gas MDL <sup>a</sup>	Soil Gas Units	Soil MDL	Soil Reporting Limit	Soil Sediment MDL	Sediment Reporting Limit	Sediment Units	Site-Specific Groundwater MDL	Groundwater Reporting Limit	Groundwater Units	Site-Specific Surface Water MDL	Surface Water Reporting Limit	Surface Water Units
<b>PHASE I: GROUNDWATER</b>															
Ferrous Iron	H8146	Field	- <sup>d</sup>	-	-	-	-	-	-	0.01	0.024	mg/L <sup>d</sup>	-	-	-
Hydrogen Sulfide	H8131	Field	-	-	-	-	-	-	-	0.001	0.005	mg/L	-	-	-
Sulfate	N-601	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.025	0.05	mg/L	-	-	-
Nitrate & Nitrite	E353.1	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.025	0.05	mg/L	-	-	-
Oxidation/Reduction Potential (ORP)	Direct-reading meter	Field	-	-	-	-	-	-	-	-	0.01	mV	-	-	-
Oxygen	Direct-reading meter	Field	-	-	-	-	-	-	-	-	0.5	%	-	-	-
pH	Direct-reading meter	Field	-	-	-	-	-	-	-	-	0.1	pH units	-	-	-
Conductivity	Direct-reading meter	Field	-	-	-	-	-	-	-	-	0.1	umhos/cm	-	-	-
Temperature	Direct-reading meter	Field	-	-	-	-	-	-	-	-	1	degrees C	-	-	-
Alkalinity	H8221	Field	-	-	-	-	-	-	-	20	20	mg/L	-	-	-
Carbon Dioxide	H8223	Field	-	-	-	-	-	-	-	0.01	1.25	mg/L	-	-	-
Chloride	N-601	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.1	0.5	mg/L	-	-	-
Methane	RSKSOP-175 & -14	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.0005	0.001	mg/L	-	-	-
Ammonia	E350.1	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.025	0.05	mg/L	-	-	-
Ethylene	RSKSOP-175 & -14	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.0025	0.003	mg/L	-	-	-
Total Organic Carbon	RSKSOP-102	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.3	0.4	mg/L	-	-	-
Total Inorganic Carbon	RSKSOP-102	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.005	0.1	mg/L	-	-	-
1,3,5-Trimethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L <sup>d</sup>	-	-	-
1,2,4-Trimethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
1,2,3-Trimethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
1,2,4,5-Tetramethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
1,2,3,5-Tetramethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
1,2,3,4-Tetramethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
Benzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
Toluene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
Ethylbenzene	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
Xylene (Total)	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	1	ug/L	-	-	-
Phenols	<sup>d</sup>	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.05	0.1	ug/L	-	-	-
Aliphatic/Aromatic Acids	RSKSOP-177	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	5	10	ug/L	-	-	-
Metals	ICAP	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.2 - 0.7	.0004 - 1.4	mg/L	-	-	-
Fuel Carbon	RSKSOP-133	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	0.5	1	ug/L	-	-	-
<b>PHASE II: SOIL, SEDIMENT, SURFACE WATER AND GROUNDWATER</b>															
Benzene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 200	ug/L	.4 - 8	.4 - 8	ug/L
Toluene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 200	ug/L	.4 - 4	.4 - 4	ug/L
Ethylbenzene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 200	ug/L	.4 - 4	.4 - 4	ug/L
Xylene (Total)	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 200	ug/L	.4 - 4	.4 - 4	ug/L
Chlorobenzene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 4	ug/L	.4 - 4	.4 - 4	ug/L
1,2,3,4-Tetramethylbenzene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.5 - 10	ug/L	1 - 10	1 - 10	ug/L
1,2,3-Trimethylbenzene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 20	ug/L	.4 - 4	.4 - 4	ug/L
1,2,4-Trimethylbenzene	SW8020/E602	Fixed-Base <sup>b</sup>	-	-	.46 - 5700	4.6 - 5700	ug/kg	.5 - 280	5 - 2800	ug/kg	.4 - 200	ug/L	.4 - 4	.4 - 4	ug/L

**TABLE 2.1**  
**ANALYTE REPORTING LIMITS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Analyte	Analytical Method	Field or Fixed-Base #	Soil		Soil		Site-Specific Sediment		Site-Specific Groundwater		Site-Specific Surface Water		Surface Water Units
			MDL #	Gas	Soil Reporting Limit	Soil Units	MDL	Reporting Limit	MDL	Reporting Limit	MDL	Reporting Limit	
1,3,5-Trimethylbenzene	SW8020/E602	Fixed-Base #	-	-	.46 - 5700	4.6 - 5700	.5 - 280	5 - 2800	.4 - 4	4 - 4	.4 - 4	4 - 4	µg/L
Acenaphthene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Anthracene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Benzo(a)anthracene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Benzo(a)pyrene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Benzo(b)fluoranthene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Benzo(g,h,i)perylene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Benzo(k)fluoranthene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Benzoic Acid	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
bis(2-Ethylhexyl)phthalate	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Chrysene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
2,4-Dichlorophenol	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
2,4-Dimethylphenol	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Fluoranthene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Fluorene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Indeno(1,2,3-cd)pyrene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
2-Methylnaphthalene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
2-Methylphenol(o-Cresol)	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
4-Methylphenol(p-Cresol)	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Naphthalene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Phenanthrene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Phenol	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
Pyrene	SW8270	Fixed-Base #	-	-	20 - 95	400 - 1900	-	-	.5 - 2	10 - 200	-	-	µg/L
<b>SOIL ONLY</b>													
Alkalinity	E310.1	Fixed-Base #	-	-	28.8 - 56.6	28.8 - 56.6	-	-	-	-	-	-	-
Iron	SW6010	Fixed-Base #	-	-	4	4	-	-	-	-	-	-	-
Nitrogen, Total Kjeldahl	E351.2	Fixed-Base #	-	-	4.9 - 9.4	4.9 - 9.4	-	-	-	-	-	-	-
pH	SW9045	Fixed-Base #	-	-	-	0.1	-	-	-	-	-	-	-
Phosphorus	SW8270	Fixed-Base #	-	-	2.8 - 4.7	2.8 - 4.7	-	-	-	-	-	-	-
TEH as Jet Fuel	M8015	Fixed-Base #	-	-	12 - 15	12 - 15	-	-	-	-	-	-	-
TVH as Gasoline	M8015	Fixed-Base #	-	-	0.1	0.1	-	-	-	-	-	-	-
<b>SOIL AND SEDIMENT</b>													
Total Organic Carbon	CO2COUL	Fixed-Base #	-	-	.05 - .09	.05 - .09	-	-	-	-	-	-	-
Total Organic Carbon	SW5030	Fixed-Base #	-	-	-	-	0.05	0.05	-	-	-	-	-
<b>GROUNDWATER ONLY</b>													
Electrical Conductivity	Direct-reading meter	Field	-	-	-	-	-	-	-	0.02	mmhos/cm	-	-
Dissolved Oxygen	Direct-reading meter	Field	-	-	-	-	-	-	-	0.5	mg/L	-	-
pH	Direct-reading meter	Field	-	-	-	-	-	-	-	0.1	pH Units	-	-
ORP	Direct-reading meter	Field	-	-	-	-	-	-	-	0.01	pE Units	-	-
Temperature	Direct-reading meter	Field	-	-	-	-	-	-	-	1	°C	-	-
Sulfate	H8051	Field	-	-	-	-	-	-	0.01	mg/L	-	-	-
Sulfide	H8131	Field	-	-	-	-	-	-	0.01	mg/L	-	-	-

**TABLE 2.1**  
**ANALYTE REPORTING LIMITS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Analyte	Analytical Method	Field or Fixed-Base	Soil Gas MDL <sup>a</sup>	Soil Gas Units	Site-Specific Soil			Site-Specific Sediment			Site-Specific Groundwater			Site-Specific Surface Water		
					MDL	Reporting Limit	Units	MDL	Reporting Limit	Units	MDL	Reporting Limit	Units	MDL	Reporting Limit	Units
Iron, Ferrous	H8146	Field	-	-	-	-	-	-	-	-	0.01	0.024	mg/L	-	-	-
Iron, Total	H8008	Field	-	-	-	-	-	-	-	-	0.01	20	mg/L	-	-	-
Alkalinity (as CaO2)	H8221	Field	-	-	-	-	-	-	-	-	0.01	1.25	mg/L	-	-	-
Carbon Dioxide	H8223	Field	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Manganese	HMAMA	Field	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Chloride	E300.0	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.024	mg/L	-	-	-
Nitrate	E300.0	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Nitrite	E300.0	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Alkalinity	E310.1	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Sulfate	E300.0	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Carbon Dioxide	COU-02	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
Methane	RSKSOP175	Fixed-Base <sup>b</sup>	-	-	-	-	-	-	-	-	0.01	0.05	mg/L	-	-	-
<b>PHASE III:</b>																
<b>SOIL GAS</b>																
Benzene	TO3	Fixed-Base <sup>b</sup>	17	ppmv	-	-	-	-	-	-	-	-	-	-	-	-
Toluene	TO3	Fixed-Base <sup>b</sup>	17	ppmv	-	-	-	-	-	-	-	-	-	-	-	-
Ethylbenzene	TO3	Fixed-Base <sup>b</sup>	17	ppmv	-	-	-	-	-	-	-	-	-	-	-	-
Xylene (Total)	TO3	Fixed-Base <sup>b</sup>	17	ppmv	-	-	-	-	-	-	-	-	-	-	-	-
O <sub>2</sub>	Direct reading meter	Field	0.5	%	-	-	-	-	-	-	-	-	-	-	-	-
CO <sub>2</sub>	Direct reading meter	Field	0.5	%	-	-	-	-	-	-	-	-	-	-	-	-
Total Petroleum Hydrocarbons	TO3	Fixed-Base <sup>b</sup>	0.034 - 170	ppmv	-	-	-	-	-	-	-	-	-	-	-	-
Total Volatile Hydrocarbons (TVH)	Direct reading meter	Field	10	ppmv	-	-	-	-	-	-	-	-	-	-	-	-

<sup>a</sup> MDL = method detection limit

<sup>b</sup> Analysis performed by USEPA National Risk Management Research Laboratory in Ada, Oklahoma

<sup>c</sup> Dash (-) = not applicable

<sup>d</sup> mg/L = milligrams per liter

<sup>e</sup> ug/L = micrograms per liter

<sup>f</sup> Standard operating procedure in preparation.

<sup>g</sup> Analysis performed by Evergreen Analytical, Inc. in Wheat Ridge, Colorado

<sup>h</sup> Analysis performed by Air Toxics Ltd. in Folsom, California

**TABLE 2.2**  
**PHASE I SAMPLE ANALYSES BY LOCATION**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Sampling Location	Sample Matrix	Analytes <sup>a</sup>																			ICAP Analytes <sup>b</sup>	Phenols	Aliphatic/Aromatic Acids	
		Aromatic VOCs	VOCs	ORP	Alkalinity	CO <sub>2</sub>	CH <sub>4</sub>	pH	Conductivity	H <sub>2</sub> S	DO	Temperature	Fe <sup>2+</sup>	Ferrous Iron	TOC	TIC	SO <sub>4</sub> <sup>-2</sup>	Sulfides	NO <sub>2</sub> <sup>-</sup> + NO <sub>3</sub> <sup>-</sup> (N)	NH <sub>3</sub>				(CH <sub>3</sub> ) <sub>2</sub>
MOC-02	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	
MOC-03	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	
MOC-04	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	
MOC-05	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	
MOC-07	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	
MOC-08	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	
MOC-11	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	
MOV-01-03	Groundwater	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-01	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-02	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-03	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-04	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-05	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-111	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-112	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
MW-113	Groundwater	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

<sup>a</sup> Refer to Table 2.1 for analytical methods, reporting units, and reporting limits.

<sup>b</sup> ICAP (Inductively coupled argon plasma) analytes include: Na, I, K, Ca, Mg, Fe, Mn, Co, Mo, Al, As, Se, Cd, Be, Cu, Cr, Ni, Zn, Ag, Ti, Pb, Li, Sr, V, Ba, B, and Ti

**Definitions:**

VOCs = Volatile Organic Compounds

CO<sub>2</sub> = Carbon dioxide

CH<sub>4</sub> = Methane

H<sub>2</sub>S = Hydrogen sulfide

DO = Dissolved Oxygen

Fe<sup>2+</sup> = Ferrous iron

TOC = Total Organic Carbon

TIC = Total Inorganic Carbon

SO<sub>4</sub><sup>-2</sup> = Sulfate

NO<sub>3</sub><sup>-</sup> = Nitrate

NO<sub>2</sub><sup>-</sup> = Nitrite

NH<sub>3</sub> = Ammonia

(CH<sub>2</sub>)<sub>2</sub> = Ethylene

ORP = Oxidation/Reduction Potential

TABLE 2.3  
PHASE II SAMPLE ANALYSES BY LOCATION  
MOGAS SITE CORRECTIVE ACTION PLAN  
RISK-BASED APPROACH TO REMEDIATION  
MYRTLE BEACH AFB, SOUTH CAROLINA

Sampling Location	Sample Matrix	Sample Depth (ft. bgs) *	Analytes *																						
			BTEX	SVOCs	Aromatic VOCs	TVH/TEH	ORP	% Moisture	Alkalinity	Chloride	CO <sub>2</sub>	CH <sub>4</sub>	N <sup>o</sup>	TKN	K	Soil pH	Conductivity	DO	GW Temperature	GW pH	Fe <sup>2+</sup>	Total Iron	TOC	Sulfate	Sulfides
AS-01	Groundwater	NA	X		X		X		X	X	X	X				X		X	X		X			X	
AS-01	Soil	4 - 6	X	X	X								X	X	X										
AS-01	Soil	6 - 8	X	X	X								X	X	X										
AS-01	Soil	12 - 14	X	X	X																				
AS-02	Groundwater	NA	X		X		X		X	X	X	X				X		X	X		X			X	
AS-02	Soil	3 - 5	X	X	X																				
AS-02	Soil	10 - 12	X	X	X								X	X		X									
MOC-02	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-03	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-04	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-05	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-07	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-08	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-10	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-11	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-12	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-13	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-19	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-20	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MOC-21	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-01	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-02	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-03	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-04	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-05	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-06	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-06	Soil	7 - 9	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-06	Soil	15 - 17	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-07	Groundwater	NA	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-07	Soil	7 - 9	X	X	X		X		X	X	X	X													
MW-07	Soil	9 - 11	X	X	X		X		X	X	X	X													
MW-07	Soil	16 - 17	X	X	X		X		X	X	X	X													
MW-08	Groundwater	NA	X		X		X		X	X	X	X						X	X		X	X		X	X
MW-08	Soil	7 - 9	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-08	Soil	11 - 13	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-08	Soil	17 - 19	X	X	X		X		X	X	X	X				X		X	X		X	X		X	X
MW-08	Soil	29 - 31	X	X	X		X		X	X	X	X													
MW-09	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-10	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-10	Soil	3 - 5	X	X	X		X		X	X	X	X													
MW-10	Soil	7 - 9	X	X	X		X		X	X	X	X													
MW-10	Soil	11 - 13	X	X	X		X		X	X	X	X													
MW-10	Soil	15 - 17	X	X	X		X		X	X	X	X													
MW-11	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-11	Soil	7 - 9	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-11	Soil	13 - 15	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-12	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-12	Soil	7 - 9	X	X	X		X		X	X	X	X													
MW-12	Soil	11 - 13	X	X	X		X		X	X	X	X													
MW-12	Soil	19 - 21	X	X	X		X		X	X	X	X													
MW-12	Soil	31 - 33	X	X	X		X		X	X	X	X													
MW-13	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-13	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-14	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-14	Soil	5 - 7	X	X	X		X		X	X	X	X													
MW-14	Soil	9 - 11	X	X	X		X		X	X	X	X													
MW-15	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-15	Soil	3 - 5	X	X	X		X		X	X	X	X													
MW-15	Soil	9 - 11	X	X	X		X		X	X	X	X													
MW-15	Soil	21 - 23	X	X	X		X		X	X	X	X													
MW-15	Soil	33 - 35	X	X	X		X		X	X	X	X													
MW-16	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-16	Soil	6 - 8	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-16	Soil	10 - 12	X	X	X		X		X	X	X	X						X	X		X	X		X	X
MW-16	Soil	20 - 22	X	X	X		X		X	X	X	X													
MW-16	Soil	32 - 34	X	X	X		X		X	X	X	X													
MW-17	Groundwater	NA	X	X	X		X		X	X	X	X						X	X		X	X		X	X

**TABLE 2.3**  
**PHASE II SAMPLE ANALYSES BY LOCATION**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Sampling Location	Sample Matrix	Sample Depth (ft. bgs) <sup>a</sup>	Analytes <sup>c</sup>																			Total Iron	Sulfate	Sulfides
			BTEX	SVOCs	Aromatic VOCs	TVH/TEH	ORP	% Moisture	Alkalinity	Chloride	CO <sub>2</sub>	CH <sub>4</sub>	N <sup>d</sup>	TKN	K	Soil pH	Conductivity	DO	GW Temperature	GW pH	Fe <sup>2+</sup>			
MW-18	Groundwater	NA	X	X	X		X		X	X	X	X				X			X		X		X	
MW-18	Soil	5 - 7	X	X	X																			
MW-18	Soil	9 - 11	X	X	X																			
MW-18	Soil	20 - 22	X	X	X																			
MW-18	Soil	32 - 34	X	X	X	X																		
MW-19	Groundwater	NA	X	X	X		X		X	X	X	X					X						X	
MW-111	Groundwater	NA	X	X	X		X		X	X	X	X					X						X	
MW-112	Groundwater	NA	X	X	X		X		X	X	X	X					X						X	
MW-113	Groundwater	NA	X	X	X		X		X	X	X	X					X						X	
VENT-01	Soil	7 - 9	X	X	X		X		X	X	X	X												
VENT-01	Soil	10 - 12	X	X	X		X		X	X	X	X												
VENT-02	Soil	7 - 9	X	X	X		X		X	X	X	X												
VENT-02	Soil	11 - 13	X	X	X		X		X	X	X	X												
SW-01	Surface Water	NA	X	X	X																			
SW-02	Surface Water	NA	X	X	X																			
SW-03	Surface Water	NA	X	X	X																			
SW-04	Surface Water	NA	X	X	X																			
SD-01	Sediment	NA	X	X	X																			
SD-02	Sediment	NA	X	X	X																			
SD-03	Sediment	NA	X	X	X																			
SD-04	Sediment	NA	X	X	X																			

<sup>a</sup> Refer to Table 2.1 for analytical methods, reporting units, and reporting limits.

<sup>b</sup> ft. bgs = feet below ground surface

<sup>c</sup> N = Nitrogen as nitrate and nitrite

<sup>d</sup> NA = not applicable

Definitions:

BTEX = Benzene, Toluene, Ethene, and Xylene

SVOCs = Semivolatile Organic Compounds

VOCs = Volatile Organic Compounds

TVH/TEH = Total Volatile Hydrocarbons/Total Extractable Hydrocarbons

CO<sub>2</sub> = Carbon dioxide

CH<sub>4</sub> = Methane

N = Nitrogen

TKN = Total Kjeldahl Nitrogen

K = Phosphorus

DO = Dissolved Oxygen

GW = groundwater

Fe<sup>2+</sup> = Ferrous Iron

TOC = Total Organic Carbon

ORP = Oxidation/Reduction Potential

**TABLE 2.4**  
**PHASE III SAMPLE ANALYSES BY LOCATION**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Sampling Location	Sample Matrix	Sample Depth (ft. bgs)	Analytes <sup>a/</sup>				
			BTEX (TO-3)	TVH (TO-3)	TVH (field meter)	O <sub>2</sub> (field meter)	CO <sub>2</sub> (field meter)
SV-01	Soil gas	NA			X	X	X
SV-02	Soil gas	NA	X	X	X	X	X
SV-03	Soil gas	NA			X	X	X
SV-04	Soil gas	NA					
SV-05	Soil gas	NA			X	X	X
SV-06	Soil gas	NA			X	X	X
SV-07	Soil gas	NA	X	X	X	X	X
SV-08	Soil gas	NA			X	X	X
VENT-01	Soil gas	NA	X	X	X	X	X
VENT-02	Soil gas	NA	X	X	X		X

<sup>a/</sup> Refer to Table 2.1 for analytical methods, reporting units, and reporting limits.

Definitions:

BTEX = Benzene, Toluene, Ethene, and Xylene

TVH = Total Volatile Hyrdocarbons

O<sub>2</sub> = Oxygen

CO<sub>2</sub> = Carbon dioxide

subsequently labeled with "MOC-" or "SV-" prefixes, respectively. Groundwater monitoring points were installed at the 13 CPT push locations identified in Section 2.1, and vapor monitoring points were installed at the four CPT push locations identified in Section 2.1, to characterize the quality of water and soil gas, respectively. The locations of these groundwater and soil vapor monitoring points and the CPT boreholes which were not converted to monitoring wells are presented on Figure 2.1. The total depth of the CPT pushes and vapor and groundwater monitoring point completion details are presented in Table 2.5 and Appendix C.

Groundwater and vapor monitoring points installed in CPT boreholes were constructed of flush-threaded 0.75-inch inside-diameter (ID) polyvinyl chloride (PVC) casing and screen that were pressed into the ground through 1.8-inch outside-diameter (OD) CPT pushrods. The screens were 3.0 feet long and factory-slotted with 0.010-inch openings. A sacrificial stainless steel CPT tip was screwed into the PVC screen and served as the bottom cap of the monitoring point. Each monitoring point was fitted with a PVC top cap upon completion. Each monitoring point was completed with a flush-mounted, at-grade protective cover with a concrete pad that slopes gently away from the protective casing to facilitate runoff during precipitation. During pad construction, the area around the monitoring point riser pipe was dug out to a depth of 1.0 to 1.5 feet and filled with concrete. Clean silica sand was poured into the annulus around each monitoring point screen; however, due to the small annular space between the monitoring point casing and the CPT rod wall, and the collapse of saturated formation sands around the monitoring point screens as the CPT rods were raised, the placement of an introduced filter pack was often only partially successful.

The manually-driven groundwater monitoring point (MOV-01-03) consisted of a 1-foot-long, 100-mesh (equivalent to an opening size of 0.006 inch) stainless steel screen connected to galvanized steel riser pipe. A stainless steel drive point was attached to the base of the screen. The IDs and ODs of the screen and riser pipe were 0.75 inch and 1.05 inches, respectively. The OD of the drive point and couplings was 1.25 inches.

### 2.2.2 Groundwater Sampling

Sixteen groundwater samples were collected at the locations listed in Section 2.1 and shown on Figure 2.1. The samples were analyzed for fuel-related contaminants and for various inorganic and geochemical indicators to evaluate natural chemical and physical attenuation processes that are occurring at the site (Table 2.2). Groundwater samples were collected using the procedures described in the work plan (Parsons ES, 1994). These procedures are in accordance with the general protocols outlined in Section 8.5 of *A Compendium of Superfund Field Methods* (USEPA, 1987).

Prior to sampling, the wells were gauged for static water levels and the presence or absence of measurable mobile LNAPL. The wells were then slowly purged using a low-flow peristaltic pump and dedicated high-density polyethylene (HDPE) tubing to minimize the agitation of the water column. During the purging process, the indicator parameters of pH, dissolved oxygen (DO), temperature, oxidation/reduction potential (ORP), and conductivity were measured using portable field instruments and a flow-

TABLE 2.5

**DRILLING AND MONITORING WELL/POINT INSTALLATION SUMMARY**  
**MOGAS CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Well ID	Groundwater Zone	Installation Date	Northing	Easting	Ground Elevation (ft msl) <sup>v</sup>	Top of Casing Elevation (ft msl)	Depth to Top of Screen (ft bgs) <sup>iv</sup>	Depth to Bottom of Screen (ft bgs)	Casing/Screen ID (Inches)	Total Depth (feet)
<b>Cone Penetrometer Boreholes</b>										
CPT-01	NA <sup>d</sup>	1/16/95	250973.44	2626789.31	19.31	NA	NA	NA	NA	26.3
CPT-06	NA	1/16/95	250862.78	2626870.95	25.05	NA	NA	NA	NA	20.4
CPT-09	NA	1/16/95	250838.89	2626743.20	24.78	NA	NA	NA	NA	20.3
CPT-14	NA	1/17/95	NS <sup>u</sup>	NS	NS	NA	NA	NA	NA	36.6
<b>Groundwater Monitoring Points</b>										
MOC-02	Shallow	1/16/95	250916.29	2626803.35	25.50	25.23	14.00	17.00	0.75	26.7
MOC-03	Shallow	1/16/95	250927.26	2626902.28	24.81	24.56	11.00	14.00	0.75	26.4
MOC-04	Shallow	1/16/95	250886.09	2626904.66	24.70	24.46	10.00	13.00	0.75	20.0
MOC-05	Shallow	1/16/95	250828.82	2626859.95	24.63	24.57	10.00	13.00	0.75	26.7
MOC-07	Shallow	1/16/95	250784.92	2626837.00	24.24	23.99	11.00	14.00	0.75	26.5
MOC-08	Shallow	1/16/95	250907.06	2626698.58	24.58	24.46	11.00	14.00	0.75	26.7
MOC-10	Shallow	1/16/95	250836.11	2626761.67	24.89	24.74	11.00	14.00	0.75	20.2
MOC-11	Shallow	1/17/95	250957.46	2626925.44	24.43	24.17	11.00	14.00	0.75	29.9
MOC-12	Shallow	1/17/95	250903.58	2627063.67	23.28	23.11	10.00	13.00	0.75	30.1
MOC-13	Shallow	1/17/95	250665.17	2626878.46	22.02	21.91	12.00	15.00	0.75	30.2
MOC-19	Shallow	1/18/95	250638.12	2626737.84	22.20	22.10	12.00	15.00	0.75	36.5
MOC-20	Shallow	1/18/95	250741.90	2626889.59	23.16	23.03	11.00	14.00	0.75	36.4
MOC-21	Shallow	1/18/95	250791.25	2626761.40	22.07	21.93	11.00	14.00	0.75	20.0
MOV-01-03	Shallow	1/18/95	NS	NS	NS	NS	2.00	3.00	0.75	3.0
<b>Groundwater Monitoring Wells</b>										
MW-01 <sup>d</sup>	Shallow	3/9/94	251010.24	2626888.95	24.92	27.72	7.20	17.20	2.00	17.8
MW-02 <sup>v</sup>	Shallow	3/26/94	250847.83	2626821.66	25.46	27.60	5.40	15.40	2.00	16.0
MW-03 <sup>v</sup>	Shallow	3/21/94	250759.54	2626674.05	20.75	22.87	4.40	14.40	2.00	15.0
MW-04 <sup>v</sup>	Shallow	3/26/94	250720.57	2626797.24	21.88	23.79	4.70	14.70	2.00	15.3
MW-05 <sup>v</sup>	Shallow	3/22/94	250834.91	2626981.43	19.81	21.93	4.30	14.30	2.00	14.9
MW-06	Shallow	8/8/95	250846.00	2626710.15	24.52	24.42	6.00	16.00	2.00	17.0
MW-07	Shallow	8/8/95	251041.05	2626777.67	25.58	25.47	5.90	15.90	2.00	17.0
MW-08	Aquitard	8/8/95	251018.63	2627088.67	23.16	23.09	19.50	29.50	2.00	31.0
MW-09	Shallow	8/8/95	251024.10	2627095.78	23.24	23.10	5.80	15.80	2.00	16.0
MW-10	Shallow	8/8/95	251151.16	2626945.50	24.01	23.83	6.00	16.00	2.00	17.0
MW-11	Shallow	8/9/95	250741.55	2626564.65	20.95	20.76	4.00	14.00	2.00	15.0
MW-12	Deep	8/9/95	250902.80	2626599.02	22.22	21.98	30.00	35.00	2.00	35.0
MW-13	Shallow	8/9/95	250909.19	2626597.96	22.13	21.93	5.00	15.00	2.00	15.0
MW-14	Shallow	8/10/95	250695.36	2626732.56	22.16	21.94	5.00	15.00	2.00	15.0
MW-15	Deep	8/10/95	251257.45	2626728.19	22.52	22.34	32.20	37.20	2.00	37.5
MW-16	Deep	8/10/95	250625.46	2626784.15	21.69	21.54	31.20	36.20	2.00	36.5
MW-17	Shallow	8/10/95	250620.63	2626788.46	21.83	21.66	5.00	15.00	2.00	15.0
MW-18	Deep	8/11/95	250666.16	2626930.33	21.36	21.28	30.00	35.00	2.00	35.0
MW-19	Shallow	8/11/95	250665.23	2626923.96	21.31	21.23	4.80	14.80	2.00	15.0

**TABLE 2.5 (continued)**  
**DRILLING AND MONITORING WELL/POINT INSTALLATION SUMMARY**  
 MOGAS CORRECTIVE ACTION PLAN  
 RISK-BASED APPROACH TO REMEDIATION  
 MYRTLE BEACH AFB, SOUTH CAROLINA

Well ID	Groundwater Zone	Installation Date	Northing	Easting	Ground Elevation (ft msl) <sup>a/</sup>	Top of Casing Elevation (ft msl)	Depth to Top of Screen <sup>b/</sup> (ft bgs)	Depth to Bottom of Screen (ft bgs)	Casing/Screen ID (inches)	Total Depth (feet)
MW-111	Shallow	11/1/88	251255.13	2626719.99	22.76	25.43	3.50	13.50	2.00	16.5
MW-112	Shallow	11/1/88	250769.69	2626740.98	19.34	22.46	3.00	13.00	2.00	16.0
MW-113	Shallow	11/1/88	250816.60	2626907.32	20.17	22.96	3.00	13.00	2.00	16.0
<b>Soil Vapor Monitoring Points</b>										
SV-01	NA	1/18/95	250902.77	2626867.71	24.98	25.31	5.00	8.00	0.75	8.0
SV-02	NA	1/18/95	250866.94	2626855.57	25.16	25.56	4.50	7.50	0.75	7.5
SV-03	NA	1/18/95	250880.15	2626841.64	25.37	25.75	4.50	7.50	0.75	7.5
SV-04	NA	1/18/95	250867.41	2626802.82	25.57	25.92	4.00	7.00	0.75	7.0
SV-05	NA	8/11/95	250840.94	2626779.36	25.01	24.93	5.00	10.00	0.75	10.0
SV-06	NA	8/11/95	250826.24	2626759.14	24.70	24.57	5.00	10.00	0.75	10.0
SV-07	NA	8/11/95	250848.58	2626747.74	24.86	24.74	5.00	10.00	0.75	10.0
SV-08	NA	8/11/95	250864.20	2626745.39	24.88	24.82	5.00	10.00	0.75	10.0
<b>Air Sparging Wells</b>										
AS-01	Shallow	8/9/95	250774.29	2626756.30	19.74	19.62	11.30	13.30	1.50	14.0
AS-02	Shallow	8/10/95	250809.51	2626886.23	21.16	20.80	10.00	12.00	1.50	12.0
<b>SVE/Bioventing Wells</b>										
VENT-01	NA	8/9/95	250859.42	2626868.62	25.03	24.60	3.50	11.00	4.00	13.0
VENT-02	NA	8/9/95	250833.59	2626749.76	24.76	24.18	3.40	10.90	4.00	13.0

a/ ft msl = feet above mean sea level

b/ ft bgs = feet below ground surface

c/ NA = not applicable

d/ NS = not surveyed

e/ Well installed during a previous investigation.

through cell. Where possible, purging was performed until 3 times the calculated casing volume was removed from each point prior to sampling, and until the pH, DO concentration, ORP, conductivity, and temperature stabilized for a 1-minute period. Field geochemical analyses were also performed for ferrous iron, hydrogen sulfide, carbon dioxide, and alkalinity using field colorimetric (Hach®) methods. Except for hydrogen sulfide, these field tests and methods are specified in the AFCEE *Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* (Wiedemeier *et al.*, 1995). The groundwater geochemical data that were collected are used to assess the biodegradation potential of dissolved COPCs and to quantitatively document chemical fate and transport processes.

Purging and sampling constituted one continuous sampling event, and there was no cessation of pumping prior to sample collection. As shown in Table 2.2, all of the samples were analyzed for anions (chloride, sulfate, nitrate, nitrite, and ammonia), aromatic VOCs, total fuel carbon, and field parameters (ORP, pH, electrical conductivity, carbon dioxide, hydrogen sulfide, total alkalinity, DO, temperature, and ferrous iron). In addition, 15 of the samples were analyzed for total organic carbon (TOC) and total inorganic carbon (TIC); nine samples were analyzed for methane and ethene; three samples were analyzed for phenols and aromatic and aliphatic acids; and all samples were analyzed for total (unfiltered) concentrations of 26 metals. All analyses except for field parameters were performed by the NRMRL in Ada, Oklahoma.

## **2.3 PHASE II - SUPPLEMENTAL SITE CHARACTERIZATION SAMPLING**

Phase II site characterization field activities were conducted by Parsons ES in August and September 1995. These activities involved permanent monitoring well installation, soil, groundwater, and drainage ditch surface water/sediment sampling, source reduction pilot test well and monitoring point installation, and aquifer testing.

### **2.3.1 Subsurface Soil Sampling**

Subsurface soil samples were collected to further characterize subsurface stratigraphy and the nature and extent of soil contamination at the MOGAS site. Soil samples were collected continuously from a majority of the boreholes and intermittently from the remaining boreholes using a truck-mounted drill rig. Samples were obtained by advancing 2- or 3-inch-diameter split-spoon sampling barrels through hollow-stem augers (ASTM Methods D1586 and D3550) in accordance with procedures outlined in the work plan (Parsons ES, 1994). These procedures conform to the general procedures outlined in Section 8.5 of *A Compendium of Superfund Field Methods* (USEPA, 1987). Alliance Environmental, Inc., a South Carolina-certified drilling contractor, performed the soil borehole and well installation. Additional soil sample collection and handling procedures are described in Appendix A of the work plan (Parsons ES, 1994).

Soil samples from all new boreholes were logged and described for lithology by the field hydrogeologist. These soil samples were field screened for organic vapors using a

standard headspace procedure and a PID calibrated to a 100-ppmv isobutylene standard. Forty-two samples from the most contaminated intervals of 14 boreholes (as determined by PID headspace measurements) were analyzed at a fixed-base laboratory.

Figure 2.2 shows the locations of all subsurface soil sampling locations. Table 2.3 presents the sample depth intervals and analytical methods for each of the locations sampled as part of this investigation at the MOGAS site. Analytical results for soil are included in tabular form in Appendix B. Borehole logs and survey data are included in Appendix C. Geological data are presented in Section 3 to characterize the physical setting of the site. Analytical results for soil are used in Sections 4 and 5 to identify soil COPCs and to characterize the nature and extent of soil contamination at the MOGAS site, and in Section 6 to estimate potential leaching effects on groundwater quality.

### 2.3.2 Monitoring Well Installation

All of the boreholes advanced at the site during Phase II were completed as groundwater monitoring wells (14), AS wells (2), SVE vent wells (2), or vapor monitoring points (4). The locations of Phase II groundwater monitoring wells (MW-06 through MW-19), AS wells (AS-01 and AS-02), vapor monitoring points (SV-05 through SV-08), and SVE wells (VENT-01 and VENT-02) are shown on Figure 2.2. Well construction information is summarized in Table 2.5, and completion diagrams for the newly installed wells and monitoring points are included in Appendix C. The monitoring and SVE wells were installed through hollow-stem augers in accordance with Appendix A of the work plan (Parsons ES, 1994). Groundwater monitoring wells were constructed using 2-inch-ID PVC screen and riser pipe. The screen slot size was 0.02 inch. A 10-20-size silica sand filter pack was placed in the annular space from the bottom of the borehole to a maximum of approximately 2 feet above the top of the screen. The filter pack was overlaid with a bentonite seal at least 2 feet thick, and a bentonite-cement grout seal was installed from the top of the bentonite seal to within 1 foot of the ground surface. The wells were completed at the ground surface with flush-mount protective casings installed in concrete. The AS wells were completed using 1.5-inch-ID, Schedule 40, flush-threaded PVC well casing and 2-foot-long stainless steel, wire-wrapped, 0.020-inch-slotted well screen. The SVE vent wells were constructed identically to the groundwater monitoring wells except that the screen and riser pipe had IDs of 4 inches.

### 2.3.3 Well Development

The newly installed groundwater monitoring wells and air sparging well AS-2 were developed using a surface-mounted centrifugal pump. The volume of water pumped during development ranged from a minimum of 30 gallons to more than 100 gallons. Development continued until the pumped water was judged to be sufficiently sediment-free, or until the water clarity did not improve significantly over time. Air sparging well AS-1 pumped dry immediately, and was not developed further.

#### 2.3.4 Groundwater Sampling

Fourteen new groundwater monitoring wells and two AS wells were installed by Parsons ES in July 1995 to monitor groundwater geochemical indicators and to delineate dissolved contaminants in groundwater at the MOGAS site. Four of the new wells (MW-12, MW-15, MW-16, and MW-18) were installed to monitor groundwater quality in the lower zone of the surficial aquifer. A fifth well, MW-08, was screened in the low permeability unit separating the upper and lower groundwater zones of the surficial aquifer. To date, a total of 17 shallow and 5 deep groundwater monitoring wells, 13 groundwater monitoring points, and 2 AS wells that are suitable for sampling have been installed at the MOGAS site.

Groundwater samples were collected from all 37 groundwater monitoring wells, monitoring points, and AS wells present at the site in August and September 1995. The groundwater samples were analyzed for fuel and nonfuel contaminants and for various inorganic and geochemical indicators to evaluate natural chemical and physical attenuation processes that are occurring at the site (Table 2.3). Well purging and groundwater sampling procedures were identical to those described in Section 2.2.2 and the work plan (Parsons ES, 1994).

Investigation activities included water level measurements, purging and sampling, and field and fixed-base analytical measurements. During the purging process, the indicator parameters of pH, DO, temperature, ORP, and specific conductivity were measured using portable field instruments. Field geochemical analyses also were performed for ferrous and total iron, sulfate, sulfide, carbon dioxide, and alkalinity using Hach field colorimetric test methods to assess the biodegradation potential of dissolved COPCs and to quantitatively document chemical fate processes.

The 37 Phase II groundwater sampling locations are shown in Figure 2.2. Field and laboratory analytical data collected at each groundwater sampling location are summarized in Table 2.3. All groundwater samples were analyzed for aromatic VOCs, including TMB and TEMB isomers by USEPA Method SW8020. USEPA Method SW8270 was used to quantify semivolatile PAH compounds in groundwater at 11 of the sampling locations. Fixed-base laboratory analyses also were performed on many of the groundwater samples for indicators of natural attenuation chemical processes. These analyses included methane, CO<sub>2</sub>, chloride, alkalinity, and nitrate/nitrite. Field analyses performed included ferrous and total iron, CO<sub>2</sub>, alkalinity, sulfate, sulfide, temperature, conductivity, DO, and ORP.

#### 2.3.5 Aquifer Testing

Parsons ES performed aquifer slug tests at seven monitoring wells, including MW-06, MW-07, MW-09, MW-10, MW-11, MW-13, and MW-17, in August 1995. Slug tests are single-well hydraulic tests used to determine the hydraulic conductivity of an aquifer in the immediate vicinity of the tested well. Slug tests provide estimates of aquifer hydraulic conductivity, which are needed to complete site hydrogeologic evaluations and to support quantitative chemical fate and transport analyses.

Both rising head and falling head tests were performed on each well. The falling head tests were performed by introducing a solid slug into the well, causing the water level in the well to rise. The decline of the water level to the equilibrium level was then measured using a pressure transducer and data logger. Following completion of the falling head test, the slug was removed from the water column, causing the water level in the well to fall. The rising head tests consisted of measuring the return (or rise) of the water levels to equilibrium levels. Data obtained from the slug tests were analyzed using the AQTESOLV® software program (Geraghty & Miller Modeling Group, 1994). This program evaluates aquifer hydraulic conductivity using the Bouwer and Rice (1976) and Bouwer (1989) solution for unconfined aquifers. The Bouwer and Rice method was used to obtain solutions for both the "falling head" (slug-in) and "rising head" (slug-out) portions of the tests.

In addition to the slug tests, a recovery test was performed in well MW-08 to allow estimation of the hydraulic conductivity of the aquitard separating the upper and lower groundwater zones. A peristaltic pump was used to lower the water level in this well by approximately 22 feet, and the recovery of the water level over time was measured. The recovery test was analyzed using the Hvorslev method presented by Fetter (1994). Slug and recovery test results are presented in Section 3 as part of the site hydrogeologic evaluation. The test data plots and results are summarized in Appendix D.

### **2.3.6 Surface Water and Sediment Sampling**

Four surface water samples (SW-01 through SW-04) were collected at the permanent surface water monitoring stations established along the drainage ditch that parallels Phylliss Drive on the south side of the MOGAS site (Figure 2.2). At each station, a 3.33-foot-long steel post was installed to mark the station locations, and the elevations of the tops of the posts were surveyed to enable surface water elevation measurements. The samples were collected along the approximate centerline of the drainage ditch to assess the impact of groundwater seeps on the surface water quality. Four ditch sediment samples also were collected in conjunction with these surface water quality samples to determine contaminant concentrations in bottom sediments along the drainage ditch. An attempt was made to measure surface water flow rates using a Pygmy® flow meter, but the flow rate was too low to register on the meter.

Surface water samples were collected directly into the sample bottle by submerging the sample bottle beneath the surface of the water in the ditch and allowing the water to slowly fill the bottle without exposure to the atmosphere. The sample bottle was capped while submerged to prevent capture of air bubbles in the sample vial. Bottom sediment samples were collected using a perforated stainless steel ladle and were rapidly transferred into the sample container, which was immediately capped to prevent VOC losses. Subsequent sample handling procedures are described in the work plan (Parsons ES, 1994). Field and laboratory analytical data collected at each of these sampling locations are summarized in Table 2.3. All surface water and sediment samples were analyzed for aromatic VOCs and TOC using methods E602 and E415.1, respectively.

### 2.3.7 Surveying

All site groundwater monitoring wells and points, CPT borehole locations not converted to monitoring points, vapor monitoring points, SVE and AS wells, and surface water/sediment monitoring stations, as well as selected site reference points, were surveyed by DDC Engineers, Inc. of North Myrtle Beach, South Carolina, following completion of all field activities. All horizontal coordinates and ground surface elevations were measured to the nearest 0.1 foot relative to a Base datum. In addition, the top-of-casing elevations (measurement datum) for all wells/points and the tops of the posts marking surface water/sediment sampling stations were surveyed to the nearest 0.01 foot to allow accurate measurement of groundwater and surface water levels at the site.

### 2.3.8 Investigation-Derived Wastes

Waste soil generated during drilling and sampling operations was containerized in labeled 55-gallon drums and staged at the POL area, located immediately west of the MOGAS site (Figure 1.3). All fluids generated from decontamination, well development, and well purging activities were similarly drummed and staged at the MOGAS site. Drummed soil was removed from the site by Southeastern Soil Recovery (SSR) for disposal. Drums of IDW water were emptied into the sanitary sewer in accordance with approved SCDHEC procedures.

## 2.4 PHASE III - SOURCE REDUCTION PILOT TESTING

Phase III field activities were conducted by Parsons ES from September 1995 through January 1996. These activities involved collecting and analyzing soil gas samples from vapor monitoring points and SVE wells and performing source reduction pilot tests using bioventing/SVE with ICE and UV oxidation off-gas treatment.

### 2.4.1 Soil Gas Measurements

Soil gas analysis was performed at the MOGAS site using both field (qualitative) and laboratory (quantitative) techniques. Prior to performing the SVE pilot test in November 1995, a limited soil gas survey was conducted to establish baseline O<sub>2</sub>, CO<sub>2</sub>, and TVH concentrations at the eight permanent vapor monitoring points (SV-01 through SV-08) and the two SVE wells (VENT-01 and VENT-02) that were installed by Parsons ES in 1995 (Figure 2.2). Field hand-held instrumentation was used to measure O<sub>2</sub>, CO<sub>2</sub>, and TVH concentrations in the soil gas at the site. All soil gas samples were field-screened using the test equipment and methods specified in the AFCEE protocol documents *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing* (Hinchee et al., 1992) and *Addendum One to Test Plan and Technical Protocol for a Field Treatability Test for Bioventing: Using Soil Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential* (Downey and Hall, 1994).

Soil gas samples for quantitative laboratory analysis were selected based on the results of the baseline field screening measurements. Four soil gas samples were

collected in laboratory-supplied SUMMA<sup>®</sup> canisters to establish quantitative baseline soil gas concentrations prior to the SVE pilot test. These samples were collected from wells VENT-01 and VENT-02 and monitoring points SV-02 and SV-07 (Figure 2.2). Additional SUMMA<sup>®</sup> canister soil gas samples were collected during the SVE pilot test to determine the influent and effluent concentrations of extracted and treated soil gas during the test. For each sampling event, the soil gas samples were analyzed using USEPA Method TO-3 for BTEX compounds and TVH referenced to gasoline by Air Toxics, Limited, in Folsom, California.

Table 2.4 identifies the field and laboratory analysis methods for each Phase III soil gas sampling location. All sample handling and field quality assurance (QA) procedures for soil gas sampling and analysis are specified in Appendix A of the work plan (Parsons ES, 1994). Analytical results for soil gas samples are summarized in Sections 4 and 5, and are presented in tabular form in Appendix B of this report.

#### 2.4.2 Source Reduction Treatability Testing

Three potentially appropriate engineered source-reduction technologies have been identified for this site. These technologies include:

- SVE to remove the high concentrations of fuel vapors accumulated beneath the site and to enhance aerobic biodegradation of fuel residuals in soils;
- *In situ* biosparging/air sparging to add DO to groundwater and the capillary fringe "smear zone" to promote VOC biodegradation in and volatilization from groundwater; and
- *In situ* bioventing, through which oxygen is introduced into the subsurface to enhance natural biodegradation of residual fuels in vadose zone soils.

A biosparging pilot test was not performed at the site, but bioventing and SVE pilot tests were performed using the two vent wells installed during Phase II field activities (VENT-01 and VENT-02, Figure 2.2). The SVE pilot test, which used off-gas treatment systems supplied by VR Systems, Inc. (a Model V2C ICE unit) and ULTROX<sup>™</sup> (a UV-oxidation treatment unit), was initiated in October 1995. The SVE systems tested and the general test procedures are described in the work plan (Parsons ES, 1994). The SVE testing was conducted over a 3-month period to evaluate the feasibility of removing VOCs and reducing the contaminant mass in the source area using this technology, and to test the VOC removal efficiencies of the ICE and ULTROX<sup>™</sup> units. SVE with ICE off-gas treatment was initiated at well VENT-01 on October 20, 1995. Once initially high soil vapor TVH concentrations near this well were reduced, the VR Systems, Inc. ICE unit was moved to VENT-02 on November 7, 1995, where it continued to operate until January 30, 1996. The ULTROX<sup>™</sup> unit was installed at VENT-01 and operated during the period from November 10 through December 20, 1995. The source reduction pilot testing of the SVE systems at the two vent wells covered a total period of approximately 100 days, with brief interruptions due to high water table conditions. Pilot test results are presented in Section 8.

A bioventing respiration test was conducted at the MOGAS site in November 1995. Significant oxygen utilization observed in these site soils indicates a very active microbial population is available to degrade fuel residuals. The potential applicability of this technology for reducing VOCs within source area soils at this site is discussed in Section 8. *In situ* bioventing can be achieved by any engineered process that increases the oxygen concentrations in unsaturated soils in order to enhance or stimulate aerobic microbial biodegradation of organic compounds. Therefore, bioventing also could be achieved during SVE and biosparging, as both of these technologies ventilate vadose zone soils with oxygen. In particular, *in situ* biosparging or air sparging is an effective mechanism to deliver oxygen-rich atmospheric air into subsurface soils at the capillary fringe. Two air sparging wells have been installed in the center of each of the dissolved contaminant plumes. The abilities of these technologies to reduce contaminant concentrations within the unsaturated soils is further evaluated in Sections 8 and 9 of this document.

## 2.5 ANALYTICAL DATA QUALITY AND MANAGEMENT

Analytical data collected during the 1995/1996 risk-based investigations were reviewed to ensure that they were suitable for use in risk analyses and met other project data quality objectives. Data management protocols followed during this CAP evaluation are summarized in this section.

All analytes that were not detected at concentrations above the MDL (see Table 2.1) were identified as not detected (U qualified) and reported by the analytical laboratory at the PQL. The MDL is defined as the minimum concentration of a substance that can be measured and reported with 99 percent confidence that the analyte concentration is greater than zero (USEPA, 1992). The MDL takes into account the reagents, sample matrix, and preparation steps applied to a sample in specific analytical methods (USEPA, 1989).

During all risk analyses for the MOGAS site, one-half the sample quantitation limits (SQLs) were selected to represent results that were below detection limits. USEPA (1989) guidance states, "Most analytes at a site are not positively detected in each sample collected and analyzed. Instead, for a particular chemical the data set generally will contain some samples with positive results and others with non-detected results. The non-detected results usually are reported as SQLs." Sample-specific quantitation limits (as surrogate values at one-half the SQL for all nondetects) are used in the risk analysis (comparison of site data to risk-based concentrations, etc.) because they take into account sample characteristics (matrix effects), sample preparation, and analytical adjustments (dilutions). When maximum site concentrations were compared to soil and groundwater RBSLs during the Tier 1 evaluation (Section 4), unusual or "aberrantly" high SQLs were carefully evaluated prior to conducting a risk evaluation using these data. Unusual or aberrantly high SQLs may be due to unavoidable matrix interferences that resulted in analytical dilutions related to other target analytes within the method. Significantly inflated SQLs for nondetected values were eliminated from statistical data computations or calculations when the SQLs were found to be more than four times the maximum detected (i.e., actual positive result) value. This is consistent with USEPA

(1989) guidance on the use of SQLs as surrogate values for nondetected results in quantitative risk analyses.

It is worth noting that SQLs in the risk analysis can be equal to or greater than the PQL or project reporting limit (PRL). This is because the PQL/PRL is a predetermined maximum reporting limit that AFCEE and the contracted laboratory have agreed upon. The SQL is actually the MDL adjusted to reflect sample-specific factors such as analytical dilution, or use of a smaller sample aliquot for analysis, due to matrix effects or the high concentration of some analytes. Therefore, there are instances when the SQL may greatly exceed the PQL/PRL, and one-half the SQL would serve as the appropriate "proxy" or surrogate concentration for the nondetected result. If the laboratory analysis did not require analytical adjustments to the sample or analysis, the SQL and PQL/PRL were the same for all nondetected target compounds.

All analytical results measured above the MDL but below the PQL were identified as quantitatively estimated (i.e., an analyte's presence was positively identified above zero), but usable, data (J qualified). All analytical results measured above the PQL were identified as detected concentrations (i.e., positive analytical results) and are quantitatively reliable, therefore qualification is not required. Detections above the PQL may, however, be qualified on the basis of other exceeded QC criteria.

Data also were subject to a usability/acceptability review that included (1) a review of chain-of-custody records, reported holding times, and reported recoveries for laboratory control samples and matrix spike/matrix spike duplicates; (2) analyzing and using laboratory and field blanks to qualify reported sample concentrations; and (3) measuring the reproducibility of laboratory analytical precision using QC samples. The data quality reviews identified no problems areas that would significantly affect the usability of the data for risk analysis. Appendix B presents the analytical results for all samples collected under this project, organized by environmental medium.

## SECTION 3

### PHYSICAL CHARACTERISTICS OF THE STUDY AREA

This section describes the physical characteristics of the MOGAS site and adjacent environs at Myrtle Beach AFB, as determined from data collected during previous site investigations and data collected by Parsons ES in 1995 as part of this RBCA field investigation. Previous data incorporated into this section are from earlier Base-wide and/or site-specific investigations [ES, 1981; Geraghty & Miller, 1985 (as summarized by ERM, 1990); ERM, 1990; Law, 1991 and 1994; the UST removals performed by Laidlaw in 1993 (as summarized by Law, 1994); Target, 1993; Parsons ES, 1995]. A summary of site characterization activities completed by Parsons ES to supplement preexisting data is presented in Section 2 of this CAP.

#### 3.1 REGIONAL TOPOGRAPHY AND SURFACE WATER HYDROLOGY

Myrtle Beach AFB is located within the Sea Island subdivision of the Atlantic Coastal Plain physiographic region, approximately 1 mile inland from the Atlantic Ocean (Fenneman and Douglas, 1930; Colquhoun, 1969). Landforms typical of this zone include hills and plains. The hills lie along and parallel to the coast, and include sand dunes and wave-cut scarps and ridges. The plains lie inland from the hills and are typically flat. The topography of the area is the result of reworked land- and marine-derived sediments deposited during fluctuations in sea level. Typical elevations at Myrtle Beach AFB range from msl to approximately 30 feet above msl (ES, 1981).

Myrtle Beach AFB lies on a strip of land bounded by the Atlantic Ocean on the southeast and the Intracoastal Waterway on the northwest. This strip of land, known as the Grand Strand, consists of the 60-mile section of coast from Winyah Bay north to the North Carolina border (Figure 1.1). The Intracoastal Waterway lies approximately 1.6 miles north-northwest of the MOGAS site and is classified as fresh water. The Atlantic Ocean lies approximately 1.6 miles southeast of the site. Crystal Lake and an unnamed wetland area are situated approximately 1.3 miles southwest of the MOGAS site (Figure 1.2).

The Grand Strand is drained by a system of streams and manmade waterways that generally discharge to the Intracoastal Waterway to the northwest or the Atlantic Ocean to the southeast. The drainage ditch bordering the MOGAS site on the south discharges to the Intracoastal Waterway approximately 2 miles north of the POL (Figure 1.2). Flooding is known to have occurred on the Grand Strand to an approximate elevation of 20 feet above msl during a 100-year flood event (ES, 1981). The majority of the MOGAS site lies above the 20-foot elevation contour and would be relatively unaffected by a 100-year flood.

In July 1992, 269 acres of wetland systems were delineated at Myrtle Beach AFB. Three general types of wetland systems, palustrine forested, palustrine emergent, and riverine, were identified (US Air Force, 1993). The palustrine forested systems are the dominant wetland community at the Base. Dominant canopy species in this system include swamp tupelo, red maple, and sweetgum. The emergent systems typically include cattails (*Typha latifolia*), various soft rushes, and sedges. Understory species in the palustrine forest system are limited to seedlings and saplings of the canopy species. Herbaceous species are very limited mainly due to overstory canopy shading (US Air Force, 1993).

The riverine wetland systems include both tidal and lower perennial systems. The lower perennial wetlands on the Base are constructed drainage ditches, similar to those present at the MOGAS site, that typically contain 1 to 2 feet of water. The tidal system also is a constructed feature that shows little or no tidal influence. These two systems contain a variety of sedges, rushes, and grasses (US Air Force, 1993).

## **3.2 REGIONAL GEOLOGY AND HYDROGEOLOGY**

### **3.2.1 Regional Geology**

Subsurface geology in the Myrtle Beach area is composed of Quaternary-, Tertiary-, and Cretaceous-aged sediments (Glowacz *et al.*, 1980). In descending order, the Quaternary units include undifferentiated Holocene sediments, the Socastee, the Canepatch, and the Waccamaw Formations. These sediments are unconsolidated in the Myrtle Beach area. The Tertiary Bear Bluff and Duplin Formations underlie the Quaternary deposits and were deposited in an open marine environment. The Duplin Formation appears as an erosional remnant of sandy limestone and calcareous silty sand of variable thickness, and may be absent in some areas. Below these sediments, in order of increasing age, are the Upper Cretaceous-aged Pee Dee, Black Creek, and Middendorf Formations. These formations represent a regressive sequence of fluvial to estuarine to open marine depositional environments.

The regional strike in the Myrtle Beach area is generally northeast-southwest, with the formations gently dipping to the southeast (ES, 1981). This gentle dip is the result of regional downwarping of the basement rock and sediments along the coast. This downwarping results in sedimentary units that tend to thicken downdip toward the coast. The sediments thin inland and outcrop in the Upper Coastal Plain, west of Myrtle Beach.

The shallow subsurface geology of the Myrtle Beach area consists of the Quaternary Age Socastee Formation and its associated units: the Myrtle Beach Barrier sediments and the Myrtle Beach Backbarrier sediments (ES, 1981). The Myrtle Beach Barrier sediments are composed of well-sorted fine to coarse dune sands with few fines. These sediments are well drained and highly permeable. Groundwater is typically encountered at depths of 5 feet bgs or less. The Myrtle Beach Backbarrier sediments are composed of sands with interlayered clays, silty sands, and clayey sands that occupy the flatlands behind the barrier zone. These sediments are typically deposited in a lagoonal or shallow estuarine environment that is periodically inundated by

washover fans during storm events. Locally, the Backbarrier sediments are underlain by the Myrtle Beach Barrier sediments. The Backbarrier sediments generally have low to moderate permeability, poor drainage, and a high water table due the large amount of fines present. The Socastee Formation has an abrupt, irregular, and unconformable contact with the underlying Canepatch Formation. The base of the Socastee is approximately 20 feet below msl at the coast and gradually grades upward to 25 feet above msl at its furthest inland extent, approximately 9 to 10 miles to the west.

### 3.2.2 Regional Hydrogeology

The regional hydrogeology of the Myrtle Beach area consists of the unconfined shallow aquifer and several confined aquifers at depth. The unconfined aquifer consists of approximately 100 feet of interlayered sediments that may include some or all of the facies belonging to the undifferentiated Holocene, Socastee, Canepatch, Waccamaw, Bear Bluff, and Duplin Formations. This hydrologic unit typically acts as a water table (unconfined) aquifer, but may be confined locally for short distances (ES, 1981). The water table is usually encountered within 5 feet of the ground surface, and the unconfined shallow aquifer is often used as a source of domestic and irrigation water. Recharge of the aquifer occurs throughout the area through infiltration of precipitation where permeable zones are exposed. The deeper confined aquifers are made up of three separate units: the Pee Dee, Black Creek, and Middendorf systems. The Pee Dee and the Black Creek systems are used extensively as sources of potable water. The Middendorf is not used as a source of potable water due to high chloride concentrations. Regionally, groundwater flows toward the Atlantic Ocean; however, the groundwater flow direction in the shallow unconfined aquifer can be affected by local topography and surface water bodies.

### 3.3 SITE LAND USE, TOPOGRAPHY, AND SURFACE WATER HYDROLOGY

Most of the MOGAS site has been heavily developed. The fenced portion of the site is paved with asphalt and contains two former office structures (Buildings 508 and 512), the former motor pool (Building 514), a vehicle wash rack (Building 507), the former fueling office (Building 513), a warehouse, and two smaller storage buildings along the eastern side of the site (Figure 1.4). The former UST areas can be recognized by the relatively unweathered asphalt pavement in the central portion of the site. Outside of the fence, along the southern, eastern, and western portions of the site, the area is vegetated with grasses, including Kentucky 31 (*Poa* spp.), creeping red fescue (*Festuca rubra*), annual rye (*Lolium temulentum*), Bermuda grass (*Cynodon dactylon*), bahia grass (*Paspalum notatum*), and Manhattan rye (*Lolium* sp.). Pine trees, including the loblolly pine (*Pinus taeda*) and longleaf pine (*P. palustris*), can also be found in this area. A pine forest bounds the site on the north and east. Within the Base boundaries, approximately 1,678 acres of land remains forested (US Air Force, 1993). Phylliss Drive and Third Street form the southern and western boundaries of the site, respectively. The northern boundary of the MOGAS site is the paved and fenced vehicle storage yard. An unnamed, intermittent drainage ditch is present outside of the fenced area along the eastern boundary of the site.

Topography in the vicinity of the MOGAS site ranges from flat to moderately steep. The MOGAS site is situated on a local topographic high that is about 25 feet above msl in the central portion of the site. Most of the MOGAS site is located within a paved, fenced area where the topography is relatively flat. South of the former UST locations the topography slopes gently to the south, then abruptly steepens along the northern bank of the drainage ditch that defines the southern boundary of the site along Phyliss Drive.

Because the MOGAS site is situated on a local topographic high, surface water runoff generally flows away from the central portion of the site in all directions through manmade drainage ditches, small swales, and storm sewers. A small intermittent, southerly flowing drainage ditch along the eastern side of the MOGAS site receives surface water runoff during storm events, and groundwater discharge during the winter months when the water table is highest. During field activities in January 1995, groundwater seepage was observed in the eastern ditch, where abundant amorphous iron hydroxide flocculant occurred. During field activities in August and September 1995, when groundwater levels were lower, this drainage ditch was dry except during heavy rainfall events. Surface water flow during precipitation events is generally high, but rapidly decreases within several hours after precipitation has ceased.

Ultimately, collected surface water runoff from the site flows into the westerly flowing drainage ditch that forms the southern boundary of the MOGAS site. Surface water in the southern drainage ditch flows west past the petroleum, oil, and lubricant (POL) site, located downstream and immediately west of the MOGAS site (Parsons ES, 1995). This drainage ditch discharges into the Intracoastal Waterway approximately 2 miles north of the site (Figure 1.2).

The SCDHEC has primary regulatory responsibility for the maintenance of water quality in the Myrtle Beach AFB area. Unclassified surface waters are subject to the use classification and numeric standards of the streams to which they are tributary (disregarding any site-specific numeric standards for that water body) (SCDHEC, 1993). The current uses of the Intracoastal Waterway, which receives discharge from the unclassified drainage ditch bordering the MOGAS site on the south, are recreation and water supply (US Air Force, 1993). SCDHEC (1993), under Regulation 68, has classified the Intracoastal Waterway segment to which the site ditch is tributary as a Class FW (freshwater) body from its confluence with the Waccamaw River to South Carolina Highway 9. Class FW waters are considered suitable for primary and secondary contact recreation, a source of drinking water supply, fishing, and the survival and propagation of a balanced indigenous aquatic community of flora and fauna (SCDHEC, 1993).

The drainage ditch south of the MOGAS site intersects the water table and appears to be a gaining surface water body, as evidenced by groundwater seepage along the banks of the ditch. As discussed further in Section 3.4.2.1, this ditch appears to significantly influence groundwater flow direction beneath the MOGAS site. During drier months when groundwater levels are lower, the rate of groundwater seepage to the drainage ditch probably decreases, but the perennial nature of the ditch, even under low-flow conditions, suggests that groundwater discharge occurs throughout the year.

Immediately downstream from the MOGAS site, the ditch flows under Third Street through a storm culvert, and drops approximately 2 feet from the lip of the culvert to the stream water level on the downstream side of the road. Below the culvert outfall on the west side of the road, storm events have widened the ditch for a distance of approximately 15 to 20 feet. The width and depth of this portion of the channel are approximately 15 to 20 feet and 3 to 5 feet, respectively, and water is present throughout the year.

The banks of the southern drainage ditch support dense grass, sedge (*Carex* spp., *Scirpus* spp.), and forb (*Andropogon virginicus* and various asters) vegetation that is maintained by the Base through regular mowing. This perennial ditch supports a variety of aquatic organisms, including fish, eels, turtles, and frogs that were observed in and near the ponded area west of Third Avenue during the field investigations. Aquatic plants and invertebrate organisms tolerant of seasonally disturbed habitat also are likely present in the ditch and pond.

One of four National Pollutant Discharge Elimination System (NPDES) monitoring stations established in on-Base drainage ditches is located in the southern drainage ditch approximately 2,500 feet west (downstream) of the MOGAS site (Figure 1.2). The permit requires water quality to be monitored quarterly for flow, oil and grease, pH, and temperature. According to the US Air Force (1993), the oil and grease concentrations at the four monitoring stations have been well below the established discharge permit limit of 15 mg/L, except on one occasion.

### **3.4 SITE GEOLOGY AND HYDROGEOLOGY**

As described in Sections 1 and 2, the shallow hydrogeology beneath the MOGAS site has been extensively investigated as a result of this RBCA study and prior investigations. Geologic and hydrogeologic data derived from these investigations are summarized in the following paragraphs.

#### **3.4.1 Lithology and Stratigraphic Relationships**

Unconsolidated deposits at the MOGAS site consist primarily of fine- to medium-grained sands interbedded with layers and lenses of silt and clay. Sands range from silty/clayey to well-sorted and clean, indicative of fluctuating episodes of low- to high-energy depositional environments and sediment source areas. Across the majority of the site, interlayered sands, silty sands, silt, and clay occur from ground surface to about 5 to 10 feet bgs. Below this stratum lies a 4- to 10-foot-thick unit of relatively clean sand. A 3- to 7-foot-thick silty sand unit occurs beneath the clean sand and overlies a 10- to 15-foot-thick calcareous silt and clay. A medium- to coarse-grained sand occurs beneath the silt and clay. The vertical extent of this sand unit is not known beneath the MOGAS site; however, it extends to at least 50 feet bgs beneath the adjacent POL site (Parsons ES, 1995).

In order to illustrate these stratigraphic relationships, hydrogeologic profiles were developed using the subsurface data derived from soil borehole and monitoring well logs of previous investigations and subsurface information obtained from CPT pushes,

soil boreholes, and monitoring wells installed during the RBCA investigations. Figure 3.1 shows the locations of these profiles. Figures 3.2 and 3.3 present hydrogeologic profiles A-A' and B-B', which are oriented approximately parallel and perpendicular to the direction of groundwater flow, respectively.

### 3.4.2 Hydrogeology

Groundwater occurs under water table (unconfined) conditions at depths between about 1 and 12 feet bgs at the MOGAS site. Groundwater depths are shallowest near the southern drainage ditch and increase with distance (north and south) from this ditch. The shallow unconfined groundwater is generally encountered at/or near the top of the uppermost clean sand stratum. A deeper groundwater zone also is present in the medium- to coarse-grained sand stratum beneath the silt and clay zone. Groundwater in this zone occurs under semiconfined to confined conditions, with the overlying silt and clay aquitard comprising the confining layer. In this report, these two water-bearing sand strata will be referred to as the shallow and deep groundwater zones of the surficial aquifer. A summary of groundwater elevation measurements made by Parsons ES is presented in Appendix C.

#### 3.4.2.1 Groundwater Flow and Gradients

Groundwater flow directions beneath the MOGAS site were estimated using potentiometric maps developed from water levels collected in August and October 1995. Potentiometric surface maps for August and October 1995 are shown for both the shallow and deep groundwater zones in Figures 3.4 through 3.7.

Figures 3.4 and 3.5 indicate that shallow-zone groundwater beneath the MOGAS site generally flows south toward the drainage ditch. Average horizontal hydraulic gradients for the portion of the site between Building 514 and the southern drainage ditch ranged from 0.006 foot per foot (ft/ft) in August 1995 to 0.009 ft/ft in October 1995.

The August and October water level data suggested the presence of a slight, localized groundwater mound beneath the entrance driveway to the fenced area. This mound may be caused by the presence of fill material in this area, which may vary in hydraulic conductivity from the surrounding native soils. Shallow groundwater flow at the MOGAS site appears to be primarily controlled by the southern drainage ditch, which acts as a discharge area for the shallow groundwater zone. This observation is supported by information presented by Strack (1989), who provides an example in which a stream penetrates one-tenth of the aquifer thickness and captures about 94 percent of the groundwater flow from its upgradient side.

Figures 3.6 and 3.7 are potentiometric surface maps for the deep groundwater zone in August and October 1995, respectively. Based on triangulation results for the four groundwater monitoring wells completed in this zone at the MOGAS site (MW-12, MW-15, MW-16, and MW-18), groundwater flows to the northwest in the deep groundwater system. This flow direction is opposite of groundwater flow within the shallow system. A northwesterly flow direction in the deep groundwater system also

was observed at the adjacent POL site (Parsons ES, 1995). The substantial differences in flow directions and hydraulic gradients between the shallow and deep groundwater zones suggests that the silty clay aquitard separating the two zones is laterally continuous and effective at minimizing hydraulic communication between the zones in the vicinity of the MOGAS and POL sites.

Horizontal hydraulic gradients for the deep groundwater system were determined from the August and October 1995 potentiometric surface maps (Figures 3.6 and 3.7). The values determined range between about 0.0003 ft/ft and 0.0005 ft/ft across the site. These gradients are about one order of magnitude lower than the horizontal hydraulic gradients observed in the shallow groundwater system. The horizontal hydraulic gradient in the deep groundwater system does not appear to be influenced by the southern drainage ditch.

Vertical hydraulic gradients were calculated from water level measurements collected at shallow and deep groundwater zone well pairs in August and October 1995 (Appendix C). These data indicate that in August 1995, there was a potential for shallow groundwater to migrate downward to the deep groundwater zone at each of the four well pairs. The magnitudes of the downward vertical gradients ranged from 0.04 to 0.19 ft/ft. In October 1995, the gradients were reversed at three of the four well pairs (MW-11/MW-12, MW-16/MW-17, and MW-18/MW-19), and there was a potential for upward flow from the deep zone to the shallow zone. The magnitudes of the upward gradients ranged from 0.04 to 0.16 ft/ft. Despite the existence of vertical gradients, the silty clay aquitard separating the shallow and deep groundwater zones probably minimizes hydraulic communication between the zones.

#### 3.4.2.2 Hydraulic Conductivity

Law (1994) performed slug tests in shallow zone monitoring wells MW-01 through MW-05. Computed hydraulic conductivities ranged from  $7.04 \times 10^{-4}$  to  $3.44 \times 10^{-3}$  centimeters per second (cm/sec) [2.1 to 9.7 feet per day (ft/day)] (Table 3.1), with a geometric mean of  $1.47 \times 10^{-3}$  cm/sec (4.2 ft/day). Each of these wells is screened near or across the water table within sand and/or silty sand.

Parsons ES performed rising and falling head slug tests in seven monitoring wells screened in the shallow groundwater zone during Phase II field activities in August 1995. The tested wells included MW-06, MW-07, MW-09, MW-10, MW-11, MW-13, and MW-17. As shown in Table 3.1, the resulting hydraulic conductivity values ranged from  $5.6 \times 10^{-4}$  to  $7.4 \times 10^{-3}$  cm/sec (1.5 to 21.0 ft/day) and averaged with a geometric mean of  $1.84 \times 10^{-3}$  cm/sec (5.21 ft/day). The overall average of the Law (1994) and Parsons ES estimated hydraulic conductivities is  $1.3 \times 10^{-3}$  cm/sec (3.6 ft/day). Hydraulic conductivity values for the deep groundwater zone were not obtained. Analysis of recovery test data obtained in well MW-08, which is screened in the silt and clay aquitard separating the upper and lower groundwater zones, yielded a hydraulic conductivity of  $2.2 \times 10^{-5}$  cm/sec (0.0067 ft/day). This value is substantially lower than the hydraulic conductivity of the upper sand zone, which supports the conclusion that the silt and clay zone is effectively minimizing hydraulic communication between the upper and lower sand zones.

**TABLE 3.1**  
**AQUIFER TEST RESULTS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Well ID	Hydraulic Conductivity (cm/sec) <sup>a/</sup>	Hydraulic Conductivity (ft/day) <sup>b/</sup>	Source
MW-01	$7.47 \times 10^{-4}$	2.1	Law (1994)
MW-02	$7.04 \times 10^{-4}$	2.0	Law (1994)
MW-03	$2.79 \times 10^{-3}$	7.9	Law (1994)
MW-04	$1.35 \times 10^{-3}$	3.8	Law (1994)
MW-05	$3.44 \times 10^{-3}$	9.7	Law (1994)
MW-06	$2.0 \times 10^{-3}$	5.7 (falling head)	Parsons ES
	$2.4 \times 10^{-3}$	6.8 (rising head)	
MW-07	$2.4 \times 10^{-3}$	6.8 (falling head)	Parsons ES
	$1.5 \times 10^{-3}$	4.3 (rising head)	
MW-08	$2.2 \times 10^{-6}$	0.0067 (recovery)	Parsons ES
MW-09	$2.3 \times 10^{-3}$	6.6 (falling head)	Parsons ES
	$1.5 \times 10^{-3}$	4.3 (rising head)	
MW-10	$6.4 \times 10^{-4}$	1.8 (falling head)	Parsons ES
	$7.4 \times 10^{-3}$	21 (rising head)	
MW-11	$2.0 \times 10^{-3}$	5.7 (falling head)	Parsons ES
	$1.7 \times 10^{-3}$	4.7 (rising head)	
MW-13	$2.2 \times 10^{-3}$	6.1 (falling head)	Parsons ES
	$5.6 \times 10^{-4}$	1.6 (rising head)	
MW-17	$2.4 \times 10^{-3}$	6.7 (falling head)	Parsons ES
	$1.7 \times 10^{-3}$	4.9 (rising head)	

a/ cm/sec = centimeters per second.

b/ ft/day = feet per day.

### 3.4.2.3 Effective Porosity

Because of the difficulty involved in accurately determining effective porosity, accepted literature values for the type of soils comprising the shallow saturated zone were used. Walton (1988) gives ranges of effective porosity for fine sand of 0.1 to 0.3. Average specific yields (approximately equivalent to effective porosity) for fine and medium sands given by Johnson (1967) were 0.21 and 0.26, respectively. A value of 0.25 was assumed for this project. This value is similar to the value of 0.3 used by Law (1994), but will result in higher computed advective groundwater velocities (Section 3.4.2.4).

### 3.4.2.4 Advective Groundwater Velocity

The advective velocity of groundwater in the direction parallel to groundwater flow is given by:

$$\bar{v} = \frac{K}{n_e} \frac{dH}{dL}$$

Where:  $\bar{v}$  = average advective groundwater velocity (seepage velocity)

$K$  = hydraulic conductivity

$dH/dL$  = gradient

$n_e$  = effective porosity.

Using this relationship in conjunction with the site-specific average hydraulic conductivity for the upper groundwater zone derived from slug tests (3.6 ft/day) and the average horizontal hydraulic gradient across the site (0.006 to 0.009 ft/ft), average advective groundwater velocities of 0.09 to 0.13 ft/day (32 to 47 feet per year) were calculated for the shallow groundwater system.

### 3.4.2.5 Groundwater Recharge

Recharge of the shallow groundwater from precipitation is expected to occur within unpaved areas and seasonally from the adjacent drainage ditches. Based on the estimated evapotranspiration (ET) rates presented in Section 3.5, the average annual recharge to the shallow groundwater zone is estimated to be approximately 11 to 14 inches per year (22 to 28 percent of average precipitation). However, ET and recharge rates can vary substantially due to variations in vegetation and the presence or absence of pavement. ET and recharge rates in the asphalt-covered portions of the MOGAS site are probably negligible.

## 3.5 CLIMATOLOGICAL CHARACTERISTICS

The climate along the coast of South Carolina is moderated by the Gulf Stream current, which brings warm water from the Gulf of Mexico. The temperatures are

fairly mild, with a mean annual maximum of 72 degrees Fahrenheit (°F) and a mean annual minimum of 53°F. The relative humidity averages about 88 percent at 4 a.m. and 62 percent at 1 p.m. Precipitation averages 49.8 inches per year, with approximately 107 days of precipitation each year. Although precipitation is spread fairly evenly throughout the year, maximum precipitation typically occurs during the summer months (July through September). The mean annual wind speed is 6 knots (Detachment 3, 3rd Weather Wing, 1942-1947 and 1949-1981). Local ET rates for Myrtle Beach AFB are not provided in the reports reviewed for this CAP. However, ET rates at Charleston AFB, which is located on the Atlantic coast approximately 85 miles south of Myrtle Beach, were calculated to be 36 to 39 inches per year (Halliburton NUS, 1993). Average temperatures and precipitation rates at Charleston AFB are similar to those at Myrtle Beach AFB; therefore, ET rates also are anticipated to be similar.

### **3.6 LAND USE**

#### **3.6.1 Site Access**

The MOGAS site is located in the central portion of the Base adjacent to Building 514 (Figures 1.2 and 1.4). Most of the MOGAS site is surrounded by a chainlink fence with a locked gate and paved with asphalt, which limits potential receptor exposure to contaminated soil and groundwater. Small portions of the site along the drainage ditch, which lie outside of the site perimeter fence, are accessible to Base maintenance personnel. In this area, exposures to contaminated surface water and shallow groundwater are possible.

#### **3.6.2 Current and Proposed Land Use**

Myrtle Beach AFB was closed in March 1993 as part of the Department of Defense Base realignment and closure activities. The Base is currently managed by the AFBCA, which is working with the Air Base Redevelopment Authority to determine future land uses. However, portions of the former Base, including the MOGAS site, are being transferred to the Redevelopment Authority. At present, the main streets on the Base are open to public access. The Base facilities remain closed to public access, but public access to restricted areas, as well as access to waters present in the Base drainage ditch system, is not tightly controlled, and therefore is possible. It is reasonably anticipated that the MOGAS site will be used for commercial and light industrial activities in the near term; however, an unrestricted status is planned for the long term. Commercial/residential use is planned south and west of the site, and recreational/residential use is planned northwest of the site (Souza, 1997).

#### **3.6.3 Water Resources**

The Myrtle Beach AFB potable water supply is derived from four deep water supply wells (wells 1, 2, 3, and 5) screened into the Pee-Dee and Black Creek aquifers. The Pee-Dee aquifer is the most important source of groundwater in the Myrtle Beach area, and is used for municipal, industrial, and domestic water supplies. The Pee-Dee aquifer is recharged principally at formation outcrops located at least 11 miles inland

from Myrtle Beach AFB. Outside of the Base, the Black Creek aquifer is no longer used for municipal and domestic water supplies in the Myrtle Beach area; it is used for irrigation. The Black Creek aquifer is also recharged principally at formation outcrops located several miles inland of Myrtle Beach. Former supply well 4 has been closed and capped (US Air Force, 1993). Each active well has a pumping capacity of 400 to 450 gallons per minute and is equipped with a chlorinator. Given the substantial depth to the Pee Dee-Black Creek aquifer system, it is unlikely that shallow contamination would migrate to these aquifers. According to ES (1981), the closest active deep well (well 1) is located across Third Street from the MOGAS site at the adjacent POL yard. Eventually, the Base will be connected to the Myrtle Beach municipal water supply system, and the wells will be used for emergency water supplies only.

### 3.7 POPULATION DEMOGRAPHICS

As a result of closure, only a small maintenance crew remains at the Base. The adjacent off-Base areas are used primarily for light commercial and industrial purposes. The nearest residential developments east and west (hydraulically cross-gradient) of the MOGAS site are located approximately 8,000 feet from the site. The nearest downgradient residential developments (toward the south) are located approximately 5,500 feet from the site.

### 3.8 ECOLOGICAL RESOURCES

The Base consists of 1,678 acres of forested lands [1,296 acres of commercial forest and 382 acres of noncommercial (i.e., recreational or aesthetic) forest], approximately 2,050 acres of developed and semi-developed land, and 126 acres of open water. Open water consists of five artificial ponds covering a total of 11 acres on the Base golf course, and a 5-acre pond in the southern portion of the Base (Figure 1.2). The cover types adjacent to the MOGAS site include urban and non-wetland forest. The developed and semi-developed urban types include regularly maintained landscaped or grassy areas along roads, ditches, and building perimeters. Common grasses found in these areas include Kentucky 31, creeping red fescue, annual rye, Bermuda, bahia and Manhattan rye. The non-wetland forest supports primarily loblolly and long-leaf pine and mixed hardwoods (US Air Force, 1993). Hydrophitic vegetation in and along the southern drainage ditch is typical of lower perennial riverine wetland systems, and is dominated by sedges, rushes, and grasses. The controlled-height restrictions across much of the Base have resulted in low species diversity in such semi-improved areas. The banks of the ditch down to the water line are covered with maintained (i.e., regularly mowed) grasses and forbs. Within the fenced portions of the MOGAS site, the cover type is urban and consists of asphalt pavement and structures, with some weed and grass growth along the perimeter of the pavement (Figure 2.1).

Terrestrial wildlife species most likely to occur on Base include the gray squirrel, fox squirrel, cottontail rabbit, marsh rabbit, white-tailed deer, raccoon, Virginia opossum, house mouse, great blue heron, mallard duck, northern bobtail quail, killdeer, mourning dove, red fox, and various songbirds, turtles, frogs, and snakes (US Air Force, 1993). Although several special-concern wildlife species could occur on the Base, only the American alligator (*Alligator mississippiensis*) could potentially occur

near the MOGAS site. This federally and state-listed threatened species has been found on a recurring basis in ponds and ditches on the Base (US Air Force, 1993). However, there is no record of alligators having been observed in the ditches near the MOGAS site.

Cover types and activity levels at and near the MOGAS site provide marginal habitat for preferred wildlife forage plant species. The lack of suitable cover and vegetation and the site perimeter security fencing effectively preclude the sustained presence of terrestrial wildlife within the fenced portions of the site. The growth of early successional stage herbaceous vegetation along the perennial drainage ditch provides some forage and cover for terrestrial and wetland species. However, the susceptibility to flooding during heavy precipitation events has limited the types and diversity of plant species and wildlife that depend on them.

The constructed, westerly flowing drainage ditch south of the site supports lower perennial riverine wetland plant communities and a variety of aquatic organisms of undetermined species. Although stressed vegetation was noted by the Air Force in the area of contaminated groundwater seepage in 1983, habitat quality along the segment of the ditch parallel to or downstream from the MOGAS site exhibited no evidence of stress during the 1995/1996 RBCA investigations in comparison to upstream segments. Small fish or minnows, turtles, frogs, eels, and snakes have been observed in the vicinity of the ponded area of the ditch downstream from the Third Street culvert. The ditch does not support a recreational or commercial fishery. The ditch could attract urban-tolerant species such as mallards, herons, and raccoon that forage on the observed aquatic fauna, particularly in the ponded area downstream from the MOGAS site.

The ditch has not been classified by SCDHEC (1993) for beneficial use. However, because the ditch discharges into the Intracoastal Waterway approximately 2 miles north of the MOGAS site, it is subject to the water quality standards associated with the surface water classification of the Intracoastal Waterway. The segment of the Intracoastal Waterway to which the site ditch is tributary has been designated a Class FW (freshwater) water body (SCDHEC, 1993). FW waters are considered suitable for a variety of uses (see Section 3.3), including survival and propagation of a balanced indigenous aquatic community of flora and fauna (SCDHEC, 1993).

## **SECTION 4**

### **TIER 1 ANALYSIS AND IDENTIFICATION OF CHEMICALS OF POTENTIAL CONCERN**

This section provides an overview of the regulatory requirements for a risk-based, tiered approach to identification of COPCs. This section also reviews the preliminary conceptual site model (CSM) developed for the MOGAS site in the CAP work plan (Parsons ES, 1994) as a means of selecting appropriate regulatory screening criteria to identify COPCs in affected site media (i.e., chemicals present at concentrations that could pose a risk to human and/or ecological receptors exposed to the affected media). This section then presents a screening-level Tier 1 analysis in accordance with SCDHEC (1995) guidance to select the COPCs that will be the focus of this CAP. The COPCs for the MOGAS site are identified in the Tier 1 analysis based on estimated risks to human health and the environment posed by maximum detected contaminant concentrations. Conservative land use and exposure assumptions are used in the Tier 1 screening analysis to ensure that the nature and extent of any COPCs that could pose a risk to human or ecological receptors at or near the site are fully described (Section 5), and that these chemicals are fully evaluated in subsequent tier analyses through quantitative fate and transport and receptor exposure evaluations (Sections 6 and 7).

#### **4.1 REGULATORY OVERVIEW OF THE TIERED APPROACH**

This section describes South Carolina's tiered approach for risk-based corrective action at petroleum release sites. Figure 4.1 illustrates the state's three-tiered approach for evaluation of petroleum releases. The approach integrates site assessment, risk assessment, risk management, monitoring, and corrective action (SCDHEC, 1995). Specifically, the remainder of Section 4 discusses the steps taken during the Tier 1 analysis. Sections 5, 6, and 7 describe subsequent tier analyses, as appropriate. In general, the tiered approach emphasizes iterative steps of site assessment, risk evaluation, and associated action decisions.

##### **4.1.1 Site Prioritization**

Based on initial contaminant release information, and subsequently upon completion of each tier evaluation, the site at which a release has occurred must be classified based on the current and projected degree of hazard to human health and the environment. A site can be classified into one of five categories. The categories, as defined in the guidance (SCDHEC, 1995), are described below:

- Category 1 (highest priority classification)--Defined as a site where the release poses an emergency (immediate health or environmental threat);
- Category 2 (second priority classification)--Defined as a site where the release poses a significant near-term (0- to 1-year) threat to human health or the environment;
- Category 3 (third priority classification)--Defined as a site where the release poses a short-term (1- to 2-year) threat to human health and the environment;
- Category 4 (fourth priority classification)--Defined as a site where the release poses a long-term (> 2-year) threat to human health and the environment; and
- Category 5 (lowest priority classification)--Defined as a site with a release that: 1) does not meet any of the characteristics of the other four categories, or 2) where there is no demonstrable threat to human health or the environment, but where data indicate that COPCs are above the Tier 1 RBSLs, and further assessment is needed.

The guidance states that prioritization is an on-going process and is based on available information. Releases may be reclassified subsequent to interim remedial actions, further assessment information, and corrective actions (SCDHEC, 1995) (see Section 4.5 for the MOGAS site classification following the Tier 1 analysis).

#### 4.1.2 Description of the Tier 1 Process

In its guidance document entitled *Risk-Based Corrective Action for Petroleum Releases* (SCDHEC, 1995), the State of South Carolina has issued screening-level target concentrations (also referred to as Tier 1 target levels or nonsite-specific RBSLs) for petroleum analytes in various media. This guidance provides a protocol for making risk-based decisions concerning corrective actions for releases of petroleum and petroleum-based products (SCDHEC, 1995). The guidance document is based on the ASTM (1995) *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites*, and is in conformance with the South Carolina UST Control Regulations 61-92, Section 280.

The state considers the Tier 1 RBSLs to be protective of human health because the values are based on conservative or maximum exposure assumptions (i.e., site chemical concentrations at or below the target levels that are not expected to cause adverse health effects in human receptors). The Tier 1 RBSLs are provided for various land use scenarios and assumptions to assist in determining site COPCs. Tier 1 soil RBSLs are presented in a "look-up" table for both residential and commercial land use scenarios. Tier 1 groundwater RBSLs also are presented in the guidance look-up tables, and are based on unrestricted groundwater use assumptions.

Although not specifically tabulated in the SCDHEC guidance, soil RBSLs (for the ingestion or dermal exposure route) based on an industrial land use scenario are available. Industrial RBSLs for many common environmental contaminants may be

obtained from USEPA Region III (1996), national, or other regional soil screening guidance (which is consistent with SCDHEC methodology), or can be calculated using simple risk assessment algorithms. The industrial land use scenario is appropriate when 1) land uses at the site and surrounding area are currently identified as industrial; 2) residential land use does not currently occur at or near the site; 3) a future residential land use scenario is unrealistic; and 4) it can be reasonably anticipated that the future use of the site will be restricted to industrial or commercial activities. The applicability of the industrial land use scenario for the MOGAS site is explained in Section 4.2.

The SCDHEC (1995) RBCA guidance does not establish RBSLs for surface water. However, the state has promulgated surface water standards for the protection of human health for certain classes of surface water, and has adopted published USEPA water quality criteria (WQC) for the protection of aquatic organisms (SCDHEC, 1993). These standards are considered to be appropriate for use as RBSLs for human and aquatic receptors exposed to surface waters affected by site contaminants (SCDHEC, 1993). SCDHEC (1995) guidance does not specify soil, air, sediment, or groundwater RBSLs for ecological receptors. In lieu of RBSLs specifically developed to be protective of plants or terrestrial wildlife, Tier 1 screening of soil, soil gas, and groundwater chemicals is conducted using only the conservative, human health-protective RBSLs, and the Tier 1 screening for surface water is conducted using both the human health and available aquatic life standards. There are no identified RBSLs for sediments; therefore, analyte concentrations detected in ditch sediments are evaluated qualitatively in Section 5.

In summary, the purpose of using SCDHEC (1995) and USEPA Region III (1996) RBSLs and SCDHEC (1993) surface water quality standards as screening tools is to focus corrective action evaluation on only those compounds and environmental media that potentially pose a threat to human health or the environment. The preliminary CSM for the MOGAS site is used to help identify the appropriate RBSLs for exposure scenarios at this site in Section 4.2. Section 4.3 presents the methodology used to select appropriate RBSLs for the MOGAS site, and Section 4.4 summarizes the analytes with site concentrations that exceed the selected RBSLs (i.e., the site COPCs). Subsequent contaminant nature and extent analysis (Section 5) is limited to those analytes whose 1995 maximum detected site concentrations exceed the conservative, matrix-specific Tier 1 screening RBSLs. Analytes with site concentrations below the health-protective screening levels are not considered to be a threat to human health or the environment (i.e., are no longer considered COPCs), and therefore are not retained for further risk/remedial analysis.

## **4.2 PRELIMINARY CONCEPTUAL SITE MODEL REVIEW**

Figure 4.2 presents a CSM based on the preliminary CSM developed for the MOGAS site in the CAP work plan (Parsons ES, 1994). The model presented in Figure 4.2 was developed using data collected during the previous site investigations and based on a review of potential receptors and feasible exposure scenarios. The purpose of developing a CSM is to evaluate available information on site characteristics, including:

- Potential contaminant sources;
- Media affected by contaminant releases;
- Mechanisms of contaminant release (e.g., leaching and volatilization);
- Potential human and ecological receptors;
- Potential receptor exposure points based on conservative, reasonable land use assumptions; and
- Routes of possible receptor exposure (e.g., inhalation, ingestion, or dermal contact).

The preliminary CSM presented in the work plan for this CAP was used to identify data gaps in site information needed to quantify exposure of receptors to site contaminants, to guide the field activities conducted during the risk-based investigation at the site, and to implement a final remedial alternative that minimizes contaminant migration and receptor exposure. The components of the preliminary CSM are described in the work plan (Parsons ES, 1994). For the purposes of the Tier 1 analysis of chemicals detected at the site, the work plan model was slightly revised (Figure 4.2) and was used to identify potentially completed receptor exposure pathways. For an exposure pathway to be completed, there must be a contaminant source, a release mechanism and a contaminant migration pathway, an exposure point, a receptor, and an exposure route. If any of these components is missing, the pathway is incomplete, and receptors are not at risk from exposure to site contaminants. Based on the preliminary CSM, air, soil, surface water, and shallow groundwater represent the affected physical media at the MOGAS site.

As discussed in Section 1.3, the former Myrtle Beach AFB is an inactive military installation located in Horry County, South Carolina, along the Atlantic Ocean coast. The runways and the eastern side of the Base have been converted for use as the Myrtle Beach Municipal Jetport under a joint-use agreement between the Base and city of Myrtle Beach. The Base occupies an area of approximately 3,793 acres on a strip of land known as the Grand Strand, and is bordered by the city of Myrtle Beach on the east and south, the Intracoastal Waterway on the north, and wetlands, timberland, and undeveloped land on the west. The surrounding land use is primarily light industrial and commercial, although some private residences are located within a few thousand feet of both the north and south Base boundaries.

As discussed earlier, the MOGAS site was the location of the former motor pool, which provided fueling and repair services for motor vehicles on the Base. The MOGAS site is approximately 425 feet by 550 feet in area, paved with asphalt, and completely surrounded by a 6-foot-high chain-link fence. Most of the MOGAS site has been heavily developed. The fenced portion of the site is paved with asphalt and contains two former office structures (Buildings 508 and 512), the former motor pool (Building 514), a vehicle wash rack (Building 507), the former fueling office (Building 513), a warehouse, and two smaller storage buildings along the eastern side of the site.

(see Figure 2.1). The former UST areas can be recognized by the relatively unweathered asphalt pavement in the central portion of the site. The eastern side of the MOGAS site is approximately 2,500 feet west of the Myrtle Beach Municipal Jetport flight line area.

As described in Section 3.6.2, it is anticipated that the MOGAS site will be used for commercial and light industrial activities in the near term; however, the long term status of the site will be unrestricted. Commercial/residential use is planned south and west of the site, and recreational/residential use is planned northwest of the site. There currently are no residential developments within 8,000 feet crossgradient from and 5,500 feet generally downgradient from the MOGAS site.

Based on these land use assumptions, onsite worker populations are the only current or likely near-term future onsite human receptors, and trespassers/recreators are potential near-term future offsite receptors who could be exposed to contaminants in the southern drainage ditch. As there is no on-Base beneficial use of groundwater from the affected shallow aquifer, current onsite workers could reasonably be exposed to air potentially affected by chemicals volatilizing from subsurface media and seeping into buildings through foundation cracks or utilities. Future workers also could include those involved in construction (e.g., during commercial-related development) or other intrusive maintenance activities. Therefore, future onsite workers could be exposed to contaminants in subsurface soils and shallow groundwater, as well as air. No potable-use exposure pathways to current off-site receptors are thought to be completed given the distance to residential and nearby commercial areas. The deep potable water wells (see Section 3.6.3) which supply the former Base area were completed beneath the affected shallow aquifer (i.e., in the Pee Dee and Black Creek deep aquifers). Completion of this exposure pathway is considered unlikely given the given the substantial depth to the Pee Dee-Black Creek aquifer system and the remote chance that shallow contamination would migrate to these aquifers.

The drainage ditch that receives contaminated groundwater discharge from the MOGAS site is accessible to the public via Phyliss Drive (Figure 2.1). Though fishing in the ditch is unlikely due to low-flow conditions during much of the year, it is possible that trespassers/recreators could be exposed to surface water in the ditch at and downstream from the site (e.g., children wading in the ditch). Therefore, there is a potentially completed exposure pathway through dermal contact and incidental ingestion from surface water to current and/or future human receptors.

Numerous plant and wildlife species are known to occur on and near the former Myrtle Beach AFB. The industrial setting and operational activity levels in the immediate site vicinity limit the presence of wildlife populations within the fenced portions of the MOGAS site. A variety of aquatic and terrestrial wildlife have been observed in the ditch, the ponded area downstream from the site below the Third Street culvert, and the maintained grassy areas along its banks near the site (see Section 3.8). The ditch and pond support aquatic vegetation typical of riverine lower perennial wetlands, but this ditch has not been identified as a jurisdictional wetland (US Air Force, 1993). For risk assessment purposes, domesticated species such as landscape grasses are not evaluated as ecological receptors (USEPA, 1994a). Moreover, the

small, vegetated areas along the ditch near the MOGAS site do not support diverse plant communities and do not provide adequate cover, foraging, or breeding/nesting habitat to sustain diverse wildlife populations. Wildlife at the site is probably limited to opportunistic, urban-tolerant feeders such as transient songbirds, raccoons, and waterfowl that may pass through the area. These animals could be exposed to contamination through ingestion of contaminated surface water and ingestion of aquatic biota associated with the contaminated segment of the ditch.

The media affected by fuel- and nonfuel-related organic contaminants at the MOGAS site, and the contaminant migration pathways and receptors discussed above were identified based on the preliminary CSM (Figure 4.2). Following the Tier 1 analysis (Section 4.3) and the quantitative fate and transport analysis presented in Section 6, a revised CSM for the site is presented in Section 7.

#### **4.3 TIER 1 SCREENING ANALYSIS**

It is the intention of the Air Force to obtain approval for a corrective action for the MOGAS site that will protect receptors from unacceptable exposures to site-related chemicals. To accomplish this objective, the COPCs that drive potential risks and impact the final remedial requirements at this site must be identified. Previous IRP site investigations (ERM, 1990; Law, 1993 and 1994; Target, 1993) and data gathered during the RBCA investigations conducted by Parsons ES in 1995 and 1996 identified the fuel-related hydrocarbons, such as the BTEX and TMB/TEMB compounds, chlorobenzene, and SVOCs, as site-related contaminants in soil, soil gas, groundwater, surface water, and sediment at the MOGAS site. Petroleum hydrocarbon releases from one or more leaking MOGAS (and possibly diesel fuel) USTs resulted in contamination of the subsurface and the adjacent downgradient drainage ditch with mobile and residual LNAPL. The four site USTs and associated piping were removed in April 1993, although much of the contaminated soil was left in place (Law, 1993).

##### **4.3.1 Selection of Appropriate Tier 1 Soil, Groundwater, Air, and Surface Water RBSLs**

South Carolina (SCDHEC, 1993 and 1995) and USEPA Region III (1996) RBSLs are based on 1) analyte-specific toxicity data; 2) an exposure-pathway-specific cancer target risk limit of  $10^{-6}$  (i.e., there is an added lifetime cancer risk for people near the site of 1 additional cancer above the normal background level in 1 million people, expressed as  $10^{-6}$  or 1 in 1 million) and a noncancer hazard quotient of less than or equal to 1; and 3) appropriate receptor scenario assumptions. Regarding the second criterion, note that USEPA (1994b) states that cancer occurs randomly within any population in the United States at a rate of about one in three persons (30-35 percent), and this is defined as "normal background level." Regarding the third criterion, appropriate receptor exposure scenario assumptions must be based on current and reasonably anticipated future land use considerations for the site, as discussed in Section 4.2.

The ultimate cleanup goal for the MOGAS site is to restore the site to a condition suitable for unrestricted use, which is the long-term plan for this site (Section 3.6.2).

However, the primary short-term cleanup goal for the MOGAS site (and the objective of this risk-based CAP) is to restore the site to a status suitable for commercial/industrial use, which is the planned near-term use of the site. Therefore, commercial and industrial RBSLs were selected as the Tier 1 soil screening values for the MOGAS site for purposes of evaluating risk from exposure to soils [the lesser of the SCDHEC (1995) and USEPA Region III (1996) was used as the comparative value]. These land use scenarios typically use less conservative exposure assumptions in calculating RBSLs compared to those used under a residential scenario. Furthermore, industrial exposure factors tend to be less conservative than those incorporated into commercial scenarios. For example, it may be assumed that there are fewer receptor visits (i.e., lower exposure frequency) to an industrial site than to a commercial site. As discussed throughout Section 4.3, commercial and industrial RBSLs were selected and compared to maximum analyte concentrations in soil. However, SCDHEC (1995) guidance suggests that exposure factors used in the soil RBSL calculations (for the ingestion and dermal exposure pathways) be based on a residential scenario. Therefore, the results of a residential-based comparison are qualitatively presented in Section 4.4.

Regarding groundwater, the former Myrtle Beach AFB currently receives its domestic (i.e., potable) water supply from deep wells screened in the Pee Dee and Black Creek aquifers (Section 3.2.2). However, the CAP risk analysis and conclusions conservatively consider and address the possibility of future unrestricted use of groundwater resources potentially impacted by the MOGAS site (i.e., unrestricted groundwater use will be assumed for the surrounding off-Base and downgradient areas). To facilitate these considerations, Tier 1 groundwater RBSLs used in this CAP are based on an assumption of unrestricted future use of groundwater. These Tier 1 RBSLs assume possible receptor exposure to site-contaminated groundwater through potable use.

SCDHEC (1995) guidance provides inhalation RBSLs for the BTEX compounds, but not for SVOCs. RBSLs for SVOCs have not been developed because of their associated low volatilities. Therefore, only BTEX RBSLs (from SCDHEC and USEPA Region III) for ambient air were evaluated in comparison to 1995 soil gas BTEX concentrations in the Tier 1 analysis.

Sediment and surface water RBSLs have not been identified in RBCA guidance from South Carolina (SCDHEC, 1995). For surface water in the drainage ditch south of the MOGAS site, state human health and aquatic life surface water quality standards for Class FW waters were used as RBSLs for Tier 1 screening (SCDHEC, 1993).

#### **4.3.1.1 RBSLs for Soil**

The industrial- and commercial-scenario RBSLs (for ingestion and dermal exposure to soils) are presented in Table 4.1 for fuel-related chemicals detected at the MOGAS site. The SCDHEC (1995) guidance provides commercial-scenario RBSLs for ingestion of, and dermal contact with, common petroleum constituents in soil. However, industrial-scenario RBSLs are not presented in the SCDHEC guidance. Therefore, generic industrial-scenario RBSLs were developed using USEPA Region

**TABLE 4.1**  
**TIER 1 SOIL CONTAMINANT**  
**SCREENING CRITERIA**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	SCDHEC	USEPA
	Commercial RBSL <sup>a/</sup> (mg/kg)	Industrial RBSL (mg/kg)
Benzene <sup>b/</sup>	99	200
Toluene <sup>b/</sup>	200000	410000
Ethylbenzene <sup>b/</sup>	100000	200000
Xylenes (Total) <sup>b/</sup>	1000000	1000000
Naphthalene <sup>b/</sup>	41000	82000
Benzo(a)anthracene <sup>b/</sup>	3.9	7.8
Benzo(b)fluoranthene <sup>b/</sup>	3.9	7.8
Benzo(g,h,i)perylene	- <sup>c/</sup>	-
Benzo(k)fluoranthene <sup>b/</sup>	39	78
Chrysene <sup>b/</sup>	390	780
Acenaphthene	-	120000
Anthracene	-	610000
Benzo(a)pyrene	-	0.78
Bis(2-ethylhexyl)phthalate	-	410
Chlorobenzene	-	41000
2,4-Dichlorophenol	-	6100
Fluoranthene	-	82000
Fluorene	-	82000
Indeno(1,2,3-cd)pyrene	-	7.8
Phenol	-	1000000
Pyrene	-	61000
1,2,4-Trimethylbenzene	-	100000
1,3,5-Trimethylbenzene	-	100000
2-Methylnaphthalene	-	-
2-Methylphenol	-	100000
4-Methylphenol	-	10000
Phenanthrene	-	-
1,2,3,4-Tetramethylbenzene	-	-
1,2,3-Trimethylbenzene	-	-

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>The lesser of the SCDHEC and USEPA values are used in comparisons with site concentrations.

<sup>c/</sup>"-" = value not available.

III's (1996) risk-based concentration tables and supplemental guidance. USEPA Region III's target soil concentrations for an industrial scenario are based on adult occupational exposure (e.g., occupational exposure frequency and duration), including an assumption that 50 percent of total incidental soil ingestion is work-related. The algorithms and assumptions used to calculate these RBSLs (with the exception of those provided in SCDHEC's look-up tables) are presented in Appendix E.

Soil RBSLs that are protective of groundwater quality (i.e., that ensure groundwater will remain suitable for potable use) also have been developed by SCDHEC (1995) and USEPA Region III (1996) (Table 4.2). These soil RBSLs are "back calculated" using groundwater RBSLs (Section 4.3.1.2) to determine the allowable contaminant leachate concentrations that can be released from soils into groundwater without causing exceedances of applicable groundwater RBSLs. Information regarding the Tier 1 soil RBSLs protective of groundwater (from SCDHEC and USEPA Region III sources) is presented in Appendix E.

#### **4.3.1.2 RBSLs for Groundwater**

RBSLs for groundwater, which are used to derive the above-mentioned target soil concentrations, are presented in Table 4.3. With the exception of the BTEX compounds, the majority of unrestricted-use groundwater RBSLs were obtained from USEPA Region III (1996) screening guidance, as the SCDHEC (1995) list is limited to target concentrations for fuel compounds. Information regarding the Tier 1 RBSLs for groundwater (from SCDHEC and USEPA Region III sources) is presented in Appendix E.

#### **4.3.1.3 RBSLs for Air**

RBSLs for air are presented in Table 4.4. As discussed earlier, the RBSL table is limited to values for BTEX compounds only. Information regarding the Tier 1 inhalation RBSLs for air (from SCDHEC and USEPA Region III sources) is presented in Appendix E.

#### **4.3.1.4 RBSLs for Surface Water**

Human health and aquatic life RBSLs for surface water are presented in Table 4.5. The RBSLs were obtained from SCDHEC (1993) and USEPA (1991) guidance. State human health and aquatic life surface water quality standards for Class FW waters were used as RBSLs for Tier 1 screening (SCDHEC, 1993). Beneficial uses of Class FW waters include primary and secondary contact recreation, drinking water supply (after conventional treatment in accordance with the requirements of SCDHEC), fishing, and survival and propagation of a balanced indigenous aquatic floral and faunal community (SCDHEC, 1993).

**TABLE 4.2**  
**TIER 1 SOIL LEACHABILITY**  
**SCREENING CRITERIA**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	SCDHEC	USEPA
	Leachability RBSL <sup>a/</sup> (mg/kg)	Leachability RBSL (mg/kg)
Benzene <sup>b/</sup>	0.007	0.016
Toluene <sup>b/</sup>	1.7	4
Ethylbenzene <sup>b/</sup>	1.5	4
Xylenes (Total) <sup>b/</sup>	44	59.2
Naphthalene <sup>b/</sup>	0.2	24
Benzo(a)anthracene <sup>b/</sup>	0.7	0.56
Benzo(b)fluoranthene <sup>b/</sup>	0.66	3.2
Benzo(k)fluoranthene <sup>b/</sup>	4.6	3.2
Chrysene <sup>b/</sup>	0.66	0.8
Acenaphthene	- <sup>c/</sup>	160
Anthracene	-	3440
Benzo(a)pyrene	-	3.2
bis(2-Ethylhexyl)phthalate	-	8.8
Chlorobenzene	-	0.48
Fluoranthene	-	784
Fluorene	-	128
Pyrene	-	1120
1,3,5-Trimethylbenzene	-	0.208
2-Methylnaphthalene	-	-
Phenanthrene	-	-
2,4-Dichlorophenol	-	0.4
2,4-Dimethylphenol	-	2.4
2-Methylphenol	-	4.8
4-Methylphenol	-	-
Benzo(g,h,i)perylene	-	-
Benzoic Acid	-	224
Indeno(1,2,3-cd)pyrene	-	28
Phenol	-	39.2
1,2,3,4-Tetramethylbenzene	-	-
1,2,3-Trimethylbenzene	-	-
1,2,4-Trimethylbenzene	-	-

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>The lesser of the SCDHEC and USEPA values are used in comparisons with site concentrations.

<sup>c/</sup>"-" = value not available.

**TABLE 4.3**  
**TIER 1 GROUNDWATER**  
**CONTAMINANT SCREENING CRITERIA**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	SCDHEC RBSL <sup>a/</sup> (µg/L)	USEPA RBSL (µg/L)
Benzene <sup>b/</sup>	5	0.36
Toluene <sup>b/</sup>	1000	750
Ethylbenzene <sup>b/</sup>	700	1300
Xylenes (Total) <sup>b/</sup>	10000	12000
Naphthalene <sup>b/</sup>	25	1500
Benzoic Acid	- <sup>c/</sup>	150000
Bis(2-ethylhexyl)phthalate	-	4.8
Chlorobenzene	-	39
1,1-Dichloroethane	-	810
2,4-Dimethylphenol	-	730
2-Methylphenol (o-Cresol)	-	1800
4-Methylphenol (p-Cresol)	-	180
Phenol	-	22000
1,2,4-Trimethylbenzene	-	300
1,3,5-Trimethylbenzene	-	300
2-Methylnaphthalene	-	-
1,2,3,4-Tetramethylbenzene	-	-
1,2,3,5-Tetramethylbenzene	-	-
1,2,4,5-Tetramethylbenzene	-	-
1,2,3-Trimethylbenzene	-	-

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>The lesser of the SCDHEC and USEPA values are used in comparisons with site concentrations.

<sup>c/</sup>"-" = value not available.

**TABLE 4.4**  
**TIER 1 AIR**  
**CONTAMINANT SCREENING CRITERIA**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	SCDHEC	USEPA
	RBSL <sup>a/</sup>	RBSL
	( $\mu\text{g}/\text{m}^3$ )	( $\mu\text{g}/\text{m}^3$ )
Benzene <sup>b/</sup>	0.22	0.22
Toluene <sup>b/</sup>	420	420
Ethylbenzene <sup>b/</sup>	1000	1000
Xylenes (Total) <sup>b/</sup>	730	7300

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>The lesser of the SCDHEC and USEPA values are used in comparisons with site concentrations.

**TABLE 4.5**  
**TIER 1 SURFACE WATER**  
**CONTAMINANT SCREENING CRITERIA**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	SCDHEC	SURROGATE USEPA
	Human Health RBSL (µg/L)	Aquatic Life RBSL (µg/L) <sup>a/</sup>
1,2,3,4-Tetramethylbenzene	-	-
1,2,3-Trimethylbenzene	-	-
1,2,4-Trimethylbenzene	-	-
1,3,5-Trimethylbenzene	-	-
Benzene	5	5,300
Toluene	1000	17,500
Chlorobenzene	488	-
Ethylbenzene	28718	32,000
Xylenes (Total)	-	-

Sources: SCDHEC, 1993; USEPA, 1991

<sup>a/</sup> The surrogate aquatic-life risk-based screening levels (RBSLs) for surface water are acute exposure USEPA (1991) lowest observed effect levels (LOELs) for protection of aquatic organisms in fresh waters.

The state aquatic life standards for surface water are adopted from published USEPA WQC (SCDHEC, 1993). However, in lieu of WQC for any of the detected surface water analytes, USEPA (1991) -reported acute-exposure, lowest-observed-effect levels (LOELs) were used as surrogate RBSLs, when available, for aquatic life screening. LOELs are available only for benzene, chlorobenzene, and ethylbenzene (Table 4.5).

#### **4.3.2 Screening to Identify COPCs in Soils, Groundwater, Soil Gas, and Surface Water**

The COPCs to be evaluated in detail in this CAP are based on a comparison of measured site concentrations to SCDHEC- and/or USEPA-approved RBSLs for soil and groundwater. As discussed above, commercial and industrial soil RBSLs and unrestricted groundwater RBSLs were selected as the appropriate set of Tier 1 screening values. Tables 4.6 through 4.11 compare the appropriate site concentrations for each compound measured during the 1995/1996 risk-based sampling events in soil, groundwater, surface water, and soil gas at the MOGAS site, to the appropriate matrix- and/or receptor-specific RBSLs. Maximum detected values are used for comparison to dermal contact/ingestion soil, groundwater, and surface water RBSLs and to surrogate aquatic life surface water RBSLs (LOELs); average site concentrations are used for comparison to soil leachability RBSLs. Soil dermal contact RBSLs are compared to both the maximum detected site soil concentrations above or below the water table (Table 4.6) and to the maximum vadose zone soil concentrations (Table 4.7). Because the long-term use of the MOGAS site is expected to be unrestricted, SCDHEC and USEPA residential RBSLs for ingestion or dermal contact with soil are also shown on Tables 4.6 and 4.7 for comparison purposes.

Maximum detected soil gas concentrations are used for comparison to RBSLs for inhalation of vapors present in ambient air. The comparison between measured soil gas concentrations to ambient air vapor RBSLs may be overly conservative. It is important to note that soil flux data were not collected at the site, nor were data available for evaluation of indoor or outdoor VOCs. Intuitively, however, soil gas measurements are suspected to potentially overestimate actual and potential indoor and outdoor ambient air concentrations. This approach was used as part of the Tier 1 analysis; however, chemical fate model results presented in Section 6 are used to determine whether any exposure pathways involving soil gas/air could be complete at the site.

#### **4.4 SUMMARY OF THE MOGAS SITE COPCS**

Table 4.12 summarizes the COPCs identified for soil, groundwater, ambient air, and surface water at the MOGAS site. Based on comparisons of the maximum site chemical concentrations to the RBSLs for ingestion and dermal exposure to soil (Tables 4.6 and 4.7) and the average site chemical concentrations to the RBSLs for potential leachability from soil to groundwater (Table 4.8), benzene, toluene, ethylbenzene, naphthalene, chlorobenzene, and 1,3,5-TMB are identified as the site COPCs in soil. These analytes are present in soils above and/or below the water table at concentrations high enough to potentially cause an exceedance of groundwater RBSLs. The average vadose zone soil concentrations are generally lower than the average site soil

**TABLE 4.6**  
**TIER 1 EVALUATION**  
**COMPARISON OF SITE SOIL CONCENTRATIONS TO DIRECT-CONTACT RBSLs**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	Units	Detected Site Maximum Concentration	Max. Conc.			Max. Conc.			Max. Conc.			Max. Conc.		
			SCDHEC Commercial RBSL <sup>a/</sup>	Exceeds Commercial RBSL	SCDHEC Residential RBSL	Exceeds Residential RBSL	USEPA Industrial RBSL	Exceeds Industrial RBSL	USEPA Residential RBSL	Exceeds Residential RBSL	USEPA Residential RBSL	Exceeds Residential RBSL	USEPA Residential RBSL	Max. Conc. Residential RBSL
Benzene	mg/kg	87	99	No	22	Yes	200	No	22	Yes	22	Yes	22	Yes
Toluene	mg/kg	650	200000	No	16000	No	410000	No	16000	No	16000	No	16000	No
Ethylbenzene	mg/kg	180	100000	No	7800	No	200000	No	7800	No	7800	No	7800	No
Xylenes (Total)	mg/kg	1000	1000000	No	160000	No	1000000	No	160000	No	160000	No	160000	No
Naphthalene	mg/kg	24	41000	No	3100	No	82000	No	3100	No	3100	No	3100	No
Benzo(a)anthracene	mg/kg	0.89	3.9	No	0.88	Yes	7.8	No	0.88	Yes	0.88	Yes	0.88	Yes
Benzo(b)fluoranthene	mg/kg	0.68	3.9	No	0.88	No	7.8	No	0.88	No	0.88	No	0.88	No
Benzo(g,h,i)perylene	mg/kg	0.13	<sup>b/</sup>	-	-	-	-	-	-	-	-	-	-	-
Benzo(k)fluoranthene	mg/kg	0.26	39	No	8.8	No	78	No	8.8	No	8.8	No	8.8	No
Chrysene	mg/kg	0.77	390	No	88	No	780	No	88	No	88	No	88	No
Acenaphthene	mg/kg	0.45	-	-	-	-	120000	No	4700	No	4700	No	4700	No
Anthracene	mg/kg	0.8	-	-	-	-	610000	No	23000	No	23000	No	23000	No
Benzo(a)pyrene	mg/kg	0.49	-	-	-	-	0.78	No	0.088	Yes	0.088	Yes	0.088	Yes
Bis(2-ethylhexyl)phthalate	mg/kg	0.03	-	-	-	-	410	No	46	No	46	No	46	No
Chlorobenzene	mg/kg	27	-	-	-	-	41000	No	1600	No	1600	No	1600	No
2,4-Dichlorophenol	mg/kg	0.36	-	-	-	-	6100	No	230	No	230	No	230	No
Fluoranthene	mg/kg	2.6	-	-	-	-	82000	No	3100	No	3100	No	3100	No
Fluorene	mg/kg	0.54	-	-	-	-	82000	No	3100	No	3100	No	3100	No
Indeno(1,2,3-cd)pyrene	mg/kg	0.18	-	-	-	-	7.8	No	0.88	No	0.88	No	0.88	No
Phenol	mg/kg	0.088	-	-	-	-	1000000	No	47000	No	47000	No	47000	No
Pyrene	mg/kg	1.9	-	-	-	-	61000	No	2300	No	2300	No	2300	No
1,2,4-Trimethylbenzene	mg/kg	650	-	-	-	-	100000	No	3900	No	3900	No	3900	No
1,3,5-Trimethylbenzene	mg/kg	220	-	-	-	-	100000	No	3900	No	3900	No	3900	No
2-Methylnaphthalene	mg/kg	30	-	-	-	-	100000	No	3900	No	3900	No	3900	No
2-Methylphenol	mg/kg	0.2	-	-	-	-	100000	No	3900	No	3900	No	3900	No
4-Methylphenol	mg/kg	0.12	-	-	-	-	10000	No	390	No	390	No	390	No
Phenanthrene	mg/kg	3	-	-	-	-	-	-	-	-	-	-	-	-
1,2,3,4-Tetramethylbenzene	mg/kg	140	-	-	-	-	-	-	-	-	-	-	-	-
1,2,3-Trimethylbenzene	mg/kg	170	-	-	-	-	-	-	-	-	-	-	-	-

Sources: SCDHEC, 1995; USEPA Region III, 1996.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>"n" = value not available.

TABLE 4.7

**TIER 1 EVALUATION**  
**COMPARISON OF VADOSE ZONE SOIL CONCENTRATIONS TO DIRECT-CONTACT RBSLs**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	Units	Detected Vadose Zone Maximum Concentration	SCDHEC		Max. Conc.		SCDHEC		Max. Conc.		USEPA		Max. Conc.		USEPA		Max. Conc.	
			Commercial	RBSL <sup>a</sup>	Exceeds	Residential	Commercial	RBSL	Industrial	RBSL	Exceeds	Residential	Industrial	RBSL	Exceeds	Residential	Industrial	RBSL
Benzene	mg/kg	0.89		99	No	22	No	200	No	22	No	410000	No	16000	No	22	No	
Toluene	mg/kg	6.2		200000	No	16000	No		No		No	200000	No	7800	No	16000	No	
Ethylbenzene	mg/kg	1.1		100000	No	7800	No		No		No	200000	No	7800	No	7800	No	
Xylenes (Total)	mg/kg	7		1000000	No	160000	No		No		No	1000000	No	160000	No	160000	No	
Naphthalene	mg/kg	1.3		41000	No	3100	No		No		No	82000	No	3100	No	3100	No	
Benzo(a)anthracene	mg/kg	0.13		3.9	No	0.88	No		No		No	7.8	No	0.88	No	0.88	No	
Benzo(b)fluoranthene	mg/kg	0.13		3.9	No	0.88	No		No		No	7.8	No	0.88	No	0.88	No	
Benzo(g,h,i)perylene	mg/kg	0.059		- <sup>b</sup>	-	-	-		-		-	-	-	-	-	-	-	
Benzo(k)fluoranthene	mg/kg	0.038		39	No	8.8	No		No		No	78	No	8.8	No	8.8	No	
Chrysene	mg/kg	0.11		390	No	88	No		-		-	780	No	88	No	88	No	
Acenaphthene	mg/kg	0.043		-	-	-	-		-		-	120000	No	4700	No	4700	No	
Anthracene	mg/kg	0.1		-	-	-	-		-		-	610000	No	23000	No	23000	No	
Benzo(a)pyrene	mg/kg	0.083		-	-	-	-		-		-	0.78	No	0.088	No	0.088	No	
Bis(2-ethylhexyl)phthalate	mg/kg	0.03		-	-	-	-		-		-	410	No	46	No	46	No	
Chlorobenzene	mg/kg	0.22		-	-	-	-		-		-	41000	No	1600	No	1600	No	
2,4-Dichlorophenol	mg/kg	0.36		-	-	-	-		-		-	6100	No	230	No	230	No	
Fluoranthene	mg/kg	0.37		-	-	-	-		-		-	82000	No	3100	No	3100	No	
Fluorene	mg/kg	0.061		-	-	-	-		-		-	82000	No	3100	No	3100	No	
Indeno(1,2,3-cd)pyrene	mg/kg	0.057		-	-	-	-		-		-	7.8	No	0.88	No	0.88	No	
Phenol	mg/kg	0.088		-	-	-	-		-		-	1000000	No	47000	No	47000	No	
Pyrene	mg/kg	0.25		-	-	-	-		-		-	61000	No	2300	No	2300	No	
1,2,4-Trimethylbenzene	mg/kg	25		-	-	-	-		-		-	100000	No	3900	No	3900	No	
1,3,5-Trimethylbenzene	mg/kg	5.6		-	-	-	-		-		-	100000	No	3900	No	3900	No	
2-Methylnaphthalene	mg/kg	2.4		-	-	-	-		-		-	100000	No	3900	No	3900	No	
2-Methylphenol	mg/kg	0.066		-	-	-	-		-		-	-	-	-	-	-	-	
4-Methylphenol	mg/kg	0.12		-	-	-	-		-		-	100000	No	3900	No	3900	No	
Phenanthrene	mg/kg	0.4		-	-	-	-		-		-	100000	No	3900	No	3900	No	
1,2,3,4-Tetramethylbenzene	mg/kg	7.2		-	-	-	-		-		-	-	-	-	-	-	-	
1,2,3-Trimethylbenzene	mg/kg	2.6		-	-	-	-		-		-	-	-	-	-	-	-	

Sources: SCDHEC, 1995; USEPA Region III, 1996.

<sup>a</sup>RBSL = risk-based screening level.<sup>b</sup>-, "-" = value not available.

**TABLE 4.8**  
**TIER 1 EVALUATION**  
**COMPARISON OF SITE SOIL CONCENTRATIONS TO SOIL LEACHABILITY RBSLs**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	Units	Average Concentration	SCDHEC Leachability RBSL <sup>a/</sup>	Avg. Conc. Exceeds SCDHEC RBSL <sup>b/</sup>	USEPA Leachability RBSL	Avg. Conc. Exceeds USEPA RBSL <sup>b/</sup>
Benzene	mg/kg	2.86	0.007	Yes	0.016	Yes
Toluene	mg/kg	23.4	1.7	Yes	4	Yes
Ethylbenzene	mg/kg	7.2	1.5	Yes	4	Yes
Xylenes (Total)	mg/kg	37	44	No	59.2	No
Naphthalene	mg/kg	4.4	0.2	Yes	24	No
Benzo(a)anthracene	mg/kg	0.153	0.7	No	0.56	No
Benzo(b)fluoranthene	mg/kg	0.127	0.66	No	3.2	No
Benzo(k)fluoranthene	mg/kg	0.063	4.6	No	3.2	No
Chrysene	mg/kg	0.136	0.66	No	0.8	No
Acenaphthene	mg/kg	0.083	- <sup>c/</sup>	-	160	No
Anthracene	mg/kg	0.130	-	-	3440	No
Benzo(a)pyrene	mg/kg	0.098	-	-	3.2	No
bis(2-Ethylhexyl)phthalate	mg/kg	0.04	-	-	8.8	No
Chlorobenzene	mg/kg	1.17	-	-	0.48	Yes
Fluoranthene	mg/kg	0.400	-	-	784	No
Fluorene	mg/kg	0.095	-	-	128	No
Pyrene	mg/kg	0.303	-	-	1120	No
1,3,5-Trimethylbenzene	mg/kg	8.3	-	-	0.208	Yes
2-Methylnaphthalene	mg/kg	5.2	-	-	-	-
Phenanthrene	mg/kg	0.448	-	-	-	-
2,4-Dichlorophenol	mg/kg	0.079	-	-	0.4	No
2,4-Dimethylphenol	mg/kg	0.042	-	-	2.4	No
2-Methylphenol	mg/kg	0.058	-	-	4.8	No
4-Methylphenol	mg/kg	0.058	-	-	-	-
Benzo(g,h,i)perylene	mg/kg	0.050	-	-	-	-
Benzoic Acid	mg/kg	0.042	-	-	224	No
Indeno(1,2,3-cd)pyrene	mg/kg	0.057	-	-	28	No
Phenol	mg/kg	0.049	-	-	39.2	No
1,2,3,4-Tetramethylbenzene	mg/kg	5.2	-	-	-	-
1,2,3-Trimethylbenzene	mg/kg	6.3	-	-	-	-
1,2,4-Trimethylbenzene	mg/kg	23	-	-	-	-

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>Analytes were retained for further evaluation if site concentrations exceed either SCDHEC or USEPA criteria.

<sup>c/</sup>"-" = value not available.

**TABLE 4.9**  
**TIER 1 EVALUATION**  
**COMPARISON OF SITE GROUNDWATER CONCENTRATIONS TO UNRESTRICTED USE**  
**RBSLs**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Detected Analyte	Units	Detected Site Maximum Concentration	SCDHEC RBSL <sup>a/</sup>	Max. Conc.	USEPA RBSL	Max. Conc.
				Exceeds SCDHEC RBSL <sup>b/</sup>		Exceeds USEPA RBSL <sup>b/</sup>
Benzene	µg/L	5960	5	Yes	0.36	Yes
Toluene	µg/L	26000	1000	Yes	750	Yes
Ethylbenzene	µg/L	2690	700	Yes	1300	Yes
Xylenes (Total)	µg/L	14000	10000	Yes	12000	Yes
Naphthalene	µg/L	490	25	Yes	1500	No
Benzoic Acid	µg/L	600	- <sup>c/</sup>	-	150000	No
Bis(2-ethylhexyl)phthalate	µg/L	3	-	-	4.8	No
Chlorobenzene	µg/L	29	-	-	39	No
1,1-Dichloroethane	µg/L	1.4	-	-	810	No
2,4-Dimethylphenol	µg/L	10	-	-	730	No
2-Methylphenol (o-Cresol)	µg/L	46	-	-	1800	No
4-Methylphenol (p-Cresol)	µg/L	97	-	-	180	No
Phenol	µg/L	24	-	-	22000	No
1,2,4-Trimethylbenzene	µg/L	2950	-	-	300	Yes
1,3,5-Trimethylbenzene	µg/L	622	-	-	300	Yes
2-Methylnaphthalene	µg/L	110	-	-	-	-
1,2,3,4-Tetramethylbenzene	µg/L	580	-	-	-	-
1,2,3,5-Tetramethylbenzene	µg/L	134	-	-	-	-
1,2,4,5-Tetramethylbenzene	µg/L	76.4	-	-	-	-
1,2,3-Trimethylbenzene	µg/L	881	-	-	-	-

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>Analytes were retained for further evaluation if site concentrations exceed either SCDHEC (1995) or USEPA (1995) criteria

<sup>c/</sup>"-" = value not available.

**TABLE 4.10**  
**TIER 1 EVALUATION**  
**COMPARISON OF SITE SOIL GAS CONCENTRATIONS TO INHALATION RBSLs**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE AFB, SOUTH CAROLINA**

<b>Detected Analyte</b>	<b>Detected Site Maximum Concentration in Soil Gas</b>	<b>SCDHEC RBSL<sup>a/</sup> For Ambient Air</b>	<b>Max. Conc. Exceeds SCDHEC RBSL<sup>b/</sup></b>	<b>USEPA RBSL For Ambient Air</b>	<b>Max. Conc. Exceeds USEPA RBSL<sup>b/</sup></b>	<b>Units</b>
Benzene	4,225,000	0.22	Yes	0.22	Yes	µg/m <sup>3</sup>
Toluene	7,660,000	420	Yes	420	Yes	µg/m <sup>3</sup>
Ethylbenzene	882,000	1,000	Yes	1,000	Yes	µg/m <sup>3</sup>
Xylenes (Total)	1,808,100	730	Yes	7,300	Yes	µg/m <sup>3</sup>

Sources: SCDHEC, 1995; USEPA Region III, 1995.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>Analytes were retained for further evaluation if site concentrations exceed either SCDHEC (1995) or USEPA (1995) criteria.

**TABLE 4.11**  
**TIER 1 EVALUATION**  
**COMPARISON OF SITE SURFACE WATER CONCENTRATIONS TO RBSLs**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE AFB, SOUTH CAROLINA**

Detected Analyte	Detected Site Maximum Concentration	SCDHEC Human Health RBSL <sup>a/</sup>	Max. Conc. Exceeds Human Health RBSL	Surrogate USEPA Aquatic Life RBSL	Max. Conc. Exceeds Aquatic Life RBSL	Units
	in Surface Water					
1,2,3,4-Tetramethylbenzene	10 U	-	-	-	-	-
1,2,3-Trimethylbenzene	11	-	-	-	-	-
1,2,4-Trimethylbenzene	38	-	-	-	-	-
1,3,5-Trimethylbenzene	4 U	-	-	-	-	-
Benzene <sup>b/</sup>	580	5	Yes	5,300	No	µg/l
Chlorobenzene	4 U	488	No	17,500	No	µg/l
Toluene	230	1,000	No	-	No	µg/l
Ethylbenzene	20	28,718	No	32,000	No	µg/l
Xylenes (Total)	100	-	-	-	-	-

Sources: SCDHEC, 1993; USEPA, 1991.

<sup>a/</sup>RBSL = risk-based screening level.

<sup>b/</sup>Analytes were retained for further evaluation if site concentrations exceed either the SCDHEC (1993) RBSL for human health or the USEPA (1991) lowest-observed effect level for acute exposure of aquatic organisms.

**TABLE 4.12**  
**LIST OF CHEMICALS OF POTENTIAL CONCERN**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Chemicals of Potential Concern	Rationale <sup>a/</sup>
<b>Soil Leachability</b>	
Benzene	1995 average concentration > SCDHEC & USEPA risk-based screening criterion
Toluene	1995 average concentration > SCDHEC & USEPA risk-based screening criterion
Ethylbenzene	1995 average concentration > SCDHEC & USEPA risk-based screening criterion
Naphthalene	1995 average concentration > SCDHEC risk-based screening criterion
Chlorobenzene	1995 average concentration > USEPA risk-based screening criterion
1,3,5-Trimethylbenzene	1995 average concentration > USEPA risk-based screening criterion
<b>Groundwater</b>	
Benzene	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Toluene	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Ethylbenzene	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Xylenes (Total)	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Naphthalene	1995 maximum site concentration > SCDHEC risk-based screening criterion
1,2,4-Trimethylbenzene	1995 maximum site concentration > USEPA risk-based screening criterion
1,3,5-Trimethylbenzene	1995 maximum site concentration > USEPA risk-based screening criterion
<b>Air</b>	
Benzene	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Toluene	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Ethylbenzene	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
Xylenes (Total)	1995 maximum site concentration > SCDHEC & USEPA risk-based screening criterion
<b>Surface Water</b>	
Benzene	1995 maximum site concentration > SCDHEC risk-based screening criterion

<sup>a/</sup> See Tables 4.6 through 4.10.

concentrations (for soils both above and below the water table) shown in Table 4.8. As a result, the only COPCs in vadose zone soils are benzene, toluene, naphthalene, and 1,3,5-TMB; average ethylbenzene and chlorobenzene concentrations in vadose zone soils did not exceed SCDHEC or USEPA leachability RBSLs. However, contaminated soils both above and below the water table represent a continuing source of groundwater contamination; therefore, all of the COPCs identified in Table 4.8 are retained for further consideration. It is important to note that maximum detected soil concentrations of these chemicals did not exceed the RBSLs for ingestion of or dermal contact with soils under either a commercial or industrial scenario (Tables 4.6 and 4.7).

The maximum detected concentrations of benzene, benzo(a)anthracene, and benzo(a)pyrene in soils above or below the water table exceeded the SCDHEC and/or USEPA residential RBSLs, but the detected concentrations were the same order of magnitude as the RBSLs (Table 4.6). No vadose zone concentrations exceeded residential RBSLs (Table 4.7). A residential scenario is considered to be highly unlikely in the near-term, and was not quantitatively evaluated in this CAP. This residential RBSL comparison was performed for comparison purposes only and has no impact on the final list of analytes retained as soil COPCs as a result of the Tier 1 screening analysis.

Based on comparisons of the maximum detected site chemical concentrations to the RBSLs for groundwater, benzene, toluene, ethylbenzene, xylenes, naphthalene, 1,2,4-TMB, and 1,3,5-TMB are identified as the groundwater COPCs (Table 4.9). All of these are fuel-related compounds thought to be directly associated with releases at the MOGAS site.

Based on comparisons of the maximum detected site soil gas concentrations (for BTEX compounds) to the RBSLs for the vapor inhalation exposure pathway, all four BTEX compounds are identified as potential ambient air COPCs (Table 4.10). Because BTEX compounds were previously identified as COPCs in both soil and groundwater, the issue of whether a comparison of soil gas concentrations (in place of absent soil flux or ambient air data) to the RBSLs for ambient air is overly conservative (health protective) or unreasonable is moot. These specific chemicals would have been retained for further Tier 2 analysis (for all media) had only a qualitative comparison been presented regarding potential contamination of air.

Based on comparisons of the maximum detected site chemical concentrations to the human health and aquatic life RBSLs for surface water, only benzene has been identified as a human health surface water COPC (Table 4.11). None of the aquatic life surrogate RBSLs were exceeded in the ditch segment sampled at the MOGAS site. Benzene is thought to be directly associated with releases at the MOGAS site.

Only those analytes with site concentrations that exceeded the commercial/industrial soil leaching RBSLs, the unrestricted-use groundwater RBSLs, the RBSLs for inhalation of soil vapors, or the human health surface water RBSLs (Table 4.12) were retained for further analysis concerning the risk-reduction requirements for the site. The nature and extent of these contaminants are described more fully in Section 5.

Quantitative fate and transport analyses and site-specific exposure estimates are conducted and presented in Sections 6 and 7 to develop site-specific Tier 2 target concentrations (i.e., SSTLs) that are sufficient to protect human health and the environment given the likely use of the land in question (i.e., industrial use only for the MOGAS site, incidental recreational use for the areas immediately downgradient, and unrestricted use further downgradient and off-Base).

#### **4.5 SITE PRIORITY CLASSIFICATION AND TIER 1 ACTION DECISION**

Based upon the Tier 1 assessment and evaluation, the MOGAS site is believed to be a Category 5 release. Although the data indicate several analytes are present in soil, soil gas, groundwater, and surface water at concentrations that exceed their respective RBSLs, no demonstrable threat to human health or the environment is believed to exist based on the likely potential for human and ecological receptor exposure at this site. To verify this classification, further tier evaluation (at a minimum, Tier 2) is warranted (SCDHEC, 1995), and is presented in Sections 5 through 7.

## **SECTION 5**

### **NATURE AND EXTENT OF CHEMICALS OF POTENTIAL CONCERN**

#### **5.1 OVERVIEW**

This section summarizes the nature and extent of COPC contamination in soil and groundwater at and downgradient from the MOGAS site. Data from earlier site characterization activities (ERM, 1990; Law, 1993 and 1994; and Target, 1993) and the 1995/1996 RBCA field investigations are included in this discussion. Discussion in this section is limited to only those chemicals that were identified as COPCs as a result of the Tier 1 screening analysis presented in Section 4 (i.e., benzene, toluene, ethylbenzene, naphthalene, chlorobenzene, and 1,3,5-TMB in soils; benzene, toluene, ethylbenzene, xylenes, naphthalene, 1,2,4,-TMB, and 1,3,5-TMB in groundwater; benzene in surface water; and benzene, toluene, ethylbenzene, and xylenes in soil gas). Although sediment samples also were collected and analyzed, Tier 1 screening criteria for sediment are not available.

#### **5.2 SOURCES OF CONTAMINATION**

The sources of subsurface contamination at the MOGAS site are the former fuel USTs. As described in Section 1.3.1, there were a total of four USTs at the site; however, the number and locations of the USTs that leaked are not known with certainty, and can only be inferred from site assessment data. Leakage was first detected in 1983, when a fuel sheen was observed on the water surface in the southern drainage ditch. The leaking UST was subsequently drained and abandoned, and all of the USTs and associated delivery lines were removed in April 1993. In 1985 and 1987, two of the three remaining tanks were removed from service due to suspected leaks indicated by routine product level measurements. Contaminant distribution data presented in this section indicate that leaking USTs were present at both the eastern and western UST locations. Based on the relatively high concentrations of BTEX in soil gas, soil, and groundwater, gasoline is believed to be the primary fuel leaked at this site.

#### **5.3 SOIL VAPOR SAMPLING RESULTS**

Soil vapor samples were collected at the MOGAS site during a 1988 soil vapor survey performed by ERM (1990), a June 1993 soil vapor survey performed by Target (1993), and during the RBCA investigation in 1995. Soil vapor analysis results are used for secondary confirmation of the nature and extent of unsaturated soil

contamination at a site. Soil vapor samples are used to obtain a better representation of soil contamination because the samples are extracted from a larger volume of soil than a discrete soil sample collected with a split spoon. Discrete soil samples are usually nonhomogeneous, and analytical results can vary greatly among subsamples collected from the same split spoon. Thus, soil vapor samples provide a valuable indication of the type and magnitude of VOC contamination in the soil.

The 26 soil vapor samples collected by ERM (1990) near and downgradient from the former USTs were analyzed for total ionizable VOCs using an HNU® PID. The screening indicated that elevated VOC concentrations occurred near the UST locations and between the USTs and the southern drainage ditch (see Appendix A).

The sampling locations and analytical results for 63 soil vapor samples collected by Target (1993) are presented in Appendix A. Benzene was detected in 39 of the 63 samples at concentrations ranging from 1.1 µg/L to 6,425 µg/L [1.1 to 6,425 milligrams per cubic meter (mg/m<sup>3</sup>)]. Benzene concentrations in 34 of the 63 samples exceeded the time-weighted-average (TWA) 8-hour permissible exposure limit (PEL) of 3.25 mg/m<sup>3</sup> defined for benzene by the Occupational Safety and Health Administration in 1989 (OSHA). (Note: The 1989 PELs were invalidated in 1992, and less conservative PELs, originally established in 1971, are currently being enforced. However, the more conservative 1989 PELs are used here for comparison purposes.) A total of seven soil gas samples had benzene concentrations in excess of 1,000 mg/m<sup>3</sup>. The SCDHEC and USEPA inhalation RBSLs for benzene both are 0.00022 mg/m<sup>3</sup> (Table 4.10). Therefore, detected 1993 benzene concentrations in soil vapor significantly exceed the RBSL.

Toluene concentrations detected in soil vapor samples by Target (1993) ranged up to 13,270 mg/m<sup>3</sup>. A total of 14 soil vapor samples collected by Target had toluene concentrations that exceeded the 1989 TWA 8-hour PEL for this compound of 375 mg/m<sup>3</sup>, and all detected toluene concentrations exceeded the SCDHEC and USEPA inhalation RBSLs for toluene of 0.42 mg/m<sup>3</sup> (Table 4.10).

Detected soil vapor concentrations of ethylbenzene were all lower than the 1989 PEL for this compound of 435 mg/m<sup>3</sup> (OSHA, 1995), with detected concentrations ranging up to 392 mg/m<sup>3</sup>. However, all ethylbenzene detections exceeded the inhalation RBSL of 1 mg/m<sup>3</sup> (Table 4.10). Detected soil vapor concentrations of xylenes ranged from 1 to 1,912 mg/m<sup>3</sup>, with concentrations in 5 of the 63 samples exceeding the 1989 OSHA PEL for this compound of 435 mg/m<sup>3</sup>, and concentrations in 30 samples exceeding the USEPA inhalation RBSL for ambient air of 7.3 mg/m<sup>3</sup> (Table 4.10).

Laboratory analytical results for BTEX in four soil vapor samples collected during the Phase III RBCA investigation in September 1995 are presented on Figure 5.1 and in Appendix B. Similar to the Target (1993) results, detected concentrations of benzene and toluene generally substantially exceeded the 1989 OSHA PELs for these compounds referenced in the preceding paragraph, while ethylbenzene and xylene concentrations did not exceed their 1989 PELs. All of the detected benzene

concentrations, and three of the four detected toluene concentrations, also exceeded the inhalation RBSLs presented in Table 4.10.

Analytical results for TVH also are presented in Appendix A (Target, 1993) and Figure 5.2 (1995/1996 laboratory and field screening results). TVH concentrations detected by Target (1993) ranged from not detected (less than 10 ppmv) to 308,300 ppmv (30.8 percent by volume). Fixed-base laboratory TVH concentrations detected in the September 1995 soil vapor samples ranged from 28,000 to 180,000 ppmv (2.8 percent to 18 percent by volume) (Figure 5.2). TVH concentrations measured in the field in October and November 1995 and January 1996 using a hand-held hydrocarbon analyzer ranged from 20 ppmv to greater than 37,000 ppmv (0.002 to greater than 3.7 percent by volume) (Figure 5.2). The lower explosive limit (LEL) for MOGAS is 1.4 percent by volume. The concentrations of TVH in the soil gas at the MOGAS site exceeded the LEL at the times of sampling.

Subsequent field TVH measurements made during the 3-month SVE pilot test that ended in January 1996 indicated steadily declining VOC levels in soil gas (Figure 5.2). For example, the field-measured TVH concentrations at soil vapor monitoring point SV-06 declined from >35,000 ppmv in October 1995, prior to the pilot test, to 3,100 ppmv, in late January 1996. Therefore, the explosive and inhalation risks posed by soil vapors have already been substantially reduced.

The TVH data, when coupled with the compound-specific soil gas data (Figure 5.1, Appendices A and B), indicate significant residual soil contamination adjacent to and immediately downgradient from the former UST locations. As a result, if future excavation of these soils proves necessary to support remedial or construction activities, appropriate air monitoring and personal protective equipment will be necessary as a minimum to ensure that soil gas VOC concentrations do not pose a potential breathing-zone risk to workers. The remedial requirements driven by this type of site contamination are considered further in Sections 7, 8, and 9 of this CAP.

#### 5.4 SOIL SAMPLING RESULTS

ERM (1990) collected eight soil samples from five soil boreholes in November 1988 and analyzed them for aromatic VOCs (all samples) and SVOCs (two samples). In April 1993, Laidlaw (reported in Law, 1993) excavated and removed the four USTs from the site. Following tank removal, four soil samples were collected from the bottom of each excavation (total of eight samples) and analyzed for BTEX. During a subsequent site investigation performed by Law (1994), two soil samples were collected for laboratory analysis of aromatic VOCs from each of 31 soil boreholes. During the Phase II RBCA investigation performed in August 1995, 42 subsurface soil samples were collected for laboratory analysis from 14 boreholes. All of the samples were analyzed for aromatic VOCs, and selected samples also were analyzed for SVOCs. Soil quality data from previous investigations are presented in Appendix A, and data from this RBCA investigation are presented in Appendix B.

The soil quality discussion presented in this section focuses on the compounds identified as COPCs in the Tier 1 analysis described in Section 4. These COPCs

include the aromatic VOCs benzene, toluene, ethylbenzene, chlorobenzene, and 1,3,5-TMB, and the SVOC naphthalene (Tables 4.8 and 4.12). None of these compounds exceeded direct-contact RBSLs listed in Tables 4.6 and 4.7. However, average measured soil concentrations (above and below the water table) exceeded the soil leachability RBSLs listed in Table 4.8. As described in Section 4.4, average vadose zone concentrations of ethylbenzene and chlorobenzene did not exceed soil leachability RBSLs.

The maximum soil BTEX concentrations detected in each soil borehole drilled at the MOGAS site during this study and previous investigations are shown on Figure 5.3. The data clearly indicate that fuel leakage occurred at both the eastern and western UST locations. Maximum BTEX concentrations detected in soil samples at or downgradient from the eastern and western UST locations were 1,917,000  $\mu\text{g/kg}$  and 1,554,000  $\mu\text{g/kg}$ , respectively. The presence of elevated BTEX concentrations in soil downgradient from (south of) the western UST location indicates that mobile LNAPL has migrated from the UST toward the drainage ditch. This observation is consistent with the prior detection of mobile LNAPL in two large-diameter wells installed by the Air Force near monitoring well MW-12. The migration pathway of the mobile LNAPL appears to be well defined by the elevated BTEX detections in wells MW-112 and AS-01, and the relatively low magnitude of BTEX detections in soil boreholes SB-27 and SB-29 (Figure 5.3). The downgradient extent of elevated BTEX concentrations in soils near the eastern UST location is not well defined by the sampling data.

The highest contaminant levels appear to be near the groundwater surface. Static water levels measured in monitoring wells/points located in the vicinity of the former USTs that penetrated significant soil contamination generally ranged between 8 and 10 feet bgs in 1995. This observation is supported by the data presented in Figure 5.4, which illustrates the distribution of soil BTEX concentrations relative to the water table. Positive and negative values on the x axis of the figure indicate distance above and below the estimated water table depth (at the time of drilling), respectively. The majority of high concentrations are within the 4-foot interval immediately above the water table. At SVE wells VENT-01 and VENT-02, BTEX concentrations ranging from 939,000  $\mu\text{g/kg}$  to 1,917,000  $\mu\text{g/kg}$  were detected in the 4-foot interval below the water table, indicating that the petroleum "smear zone" bordering the water table that resulted from the migration of mobile LNAPL extends both above and below the water table. The vertical extent of soil contamination described above is consistent with the depths of the former USTs, which reportedly ranged from approximately 6 to 10 feet bgs. The individual horizontal distributions of benzene, toluene, and ethylbenzene in soil are similar to that depicted for total BTEX in soil in Figure 5.3.

Figure 5.3 depicts soil data obtained from both saturated zone and vadose zone samples. The extent and magnitude of vadose zone soil BTEX contamination is depicted on Figure 5.5. This figure includes BTEX data for samples collected from the vadose zone or across the water table at the time of drilling; data for samples collected from intervals that were wholly below the water table at the time of drilling are not included. Comparison of Figures 5.3 and 5.5 indicates that they are very similar. The only differences between the two figures are that the maximum soil BTEX concentrations for MW-112, Vent-01, and Vent-02 are lower on Figure 5.5. As a

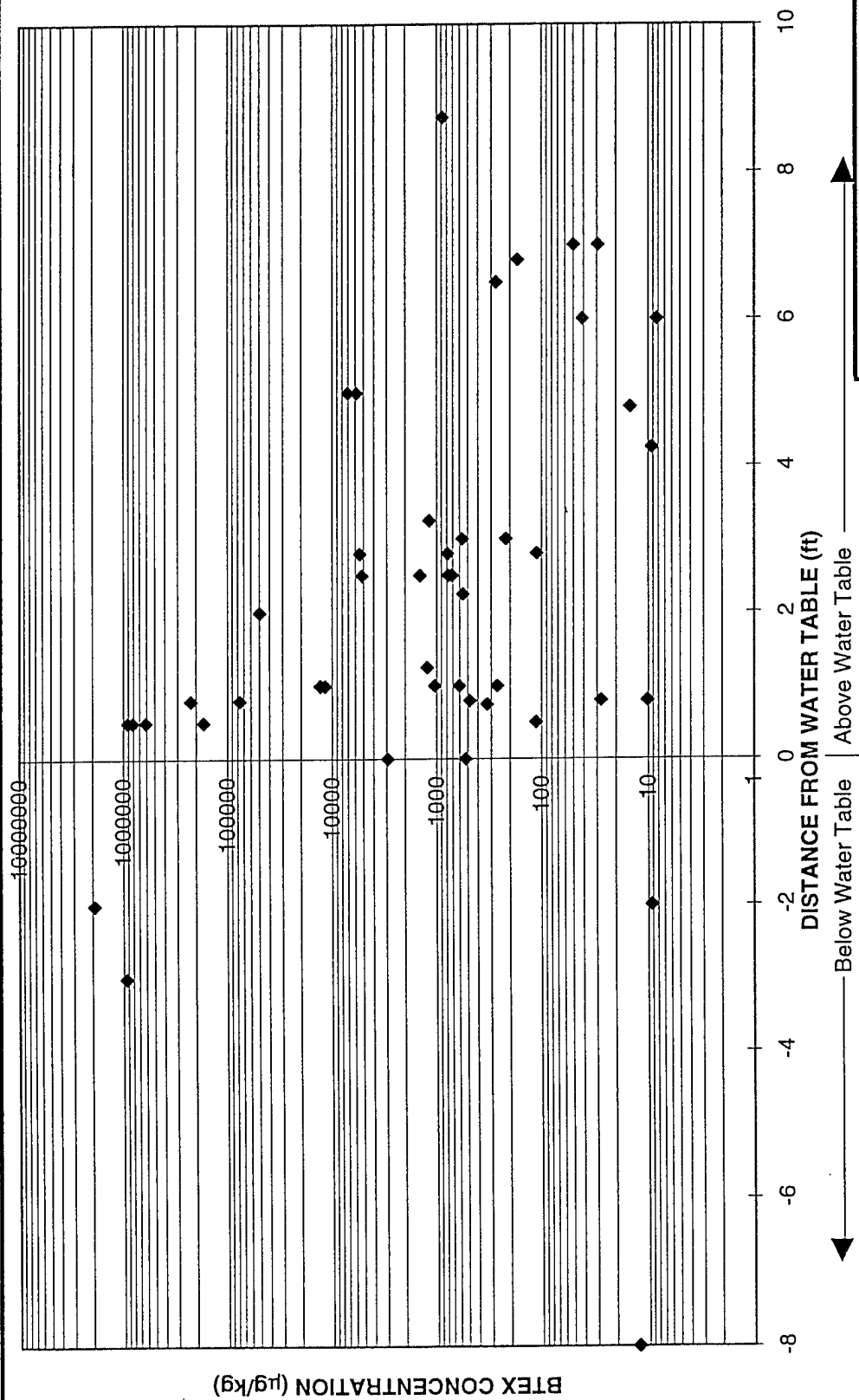


FIGURE 5.4

**SOIL BTEX CONCENTRATION VERSUS  
DISTANCE FROM WATER TABLE**

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**  
Denver, Colorado

result, the 10,000 µg/kg soil BTEX isopleth on Figure 5.5 does not extend to the drainage ditch, but terminates north of MW-112.

Chlorobenzene and 1,3,5-TMB also are identified as soil COPCs (Table 4.8) on the basis of 1995 RBCA analytical results for samples collected above and below the water table. The soil samples collected during the 1993 UST excavations (reported in Law, 1993) and in 1994 by Law (1994) were not analyzed for chlorobenzene or 1,3,5-TMB. Soil samples collected in 1988 by ERM (1990) were analyzed for chlorobenzene but not for 1,3,5-TMB. Chlorobenzene was not detected in the 1988 samples. As described in Section 4.4, average chlorobenzene concentrations in vadose zone soils do not exceed soil leaching RBSLs.

The samples collected in 1995 for this RBCA investigation were analyzed for both chlorobenzene and 1,3,5-TMB. The 1995 distributions of chlorobenzene and 1,3,5-TMB in soil are shown in Figures 5.6 and 5.7, respectively. Soil quality data suggest that substantially elevated chlorobenzene concentrations are limited in lateral extent to the immediate vicinity of the former UST locations, and in vertical extent to near and slightly below the water table. Maximum chlorobenzene concentrations detected near the former USTs at wells VENT-01 and VENT-02 were 20,000 µg/kg and 27,000 µg/kg, respectively at depths between 10 and 13 feet bgs (Figure 5.6). Chlorobenzene concentrations detected in shallower soils (7 to 9 feet bgs) were substantially lower. The maximum chlorobenzene concentration detected near the southern drainage ditch at well AS-01, located downgradient from the western UST location, was also low (39 µg/kg), and this compound was not detected at well MW-112, where substantially elevated BTEX concentrations were detected.

The two highest detections of 1,3,5-TMB occurred below the water table at SVE wells VENT-01 (220,000 µg/kg) and VENT-02 (110,000 µg/kg), located immediately downgradient from (south of) the eastern and western UST locations, respectively (Figure 5.7). Elevated 1,3,5-TMB concentrations extend south from the western UST location to near the southern drainage ditch, as evidenced by the detection of 1,3,5-TMB at a concentration of 5,600 µg/kg at well AS-01. The southern extent of elevated 1,3,5-TMB concentrations downgradient from the eastern UST location is not defined by the available data.

The only soil samples collected in 1988 by ERM (1990) that were analyzed for the COPC naphthalene were two cuttings samples obtained during drilling of soil borehole B-216 and monitoring well MW-112. Soil samples collected in 1993 during the UST excavations and in 1994 by Law (1994) were not analyzed for naphthalene.

The distribution of naphthalene in soil samples is depicted on Figure 5.8. Similar to chlorobenzene and 1,3,5-TMB, the highest naphthalene concentrations were detected in saturated zone soil from wells VENT-01 and VENT-02 at depths of 10 to 12 feet and 11 to 13 feet bgs, respectively. These wells are located immediately south of (downgradient from) the UST locations, and the elevated naphthalene detections confirm the presence of a residual petroleum smear zone that extends below the water table. Substantially elevated concentrations of naphthalene (5,100 µg/kg) also were detected in the cuttings sample from well MW-112 obtained in 1988 by ERM (1990).

This detection indicates that residual LNAPL containing naphthalene extends from the former UST location to near the drainage ditch.

## **5.5 GROUNDWATER SAMPLING RESULTS**

The COPC results from groundwater sampling events conducted during previous site investigations are summarized in this section; pertinent figures and tables detailing previous groundwater quality sampling results are contained in Appendix A. The results of the August-September 1995 sampling event performed as part of this RBCA investigation are described in detail in this section, and a complete listing of 1995 groundwater quality data is contained in Appendix B. As shown in Tables 4.9 and 4.12, the groundwater COPCs at the MOGAS site identified during the Tier 1 analysis include the BTEX compounds, naphthalene, 1,2,4-TMB, and 1,3,5-TMB. Therefore, the discussions in this section focus on these compounds.

### **5.5.1 LNAPL**

As described in Section 1.3.1, Base personnel observed a fuel sheen on surface water in the southern drainage ditch in 1983, indicating that mobile LNAPL may be migrating to the ditch from the former UST location(s). Two corrugated steel observation wells were subsequently installed at the site approximately 15 to 25 feet southwest of well MW-112 (Figure 1.4), and mobile LNAPL was observed on the groundwater surface in the wells. According to ERM (1990), a mobile LNAPL layer also was observed in well MW-112 during sampling activities in 1988, and a petroleum sheen was noted on the groundwater seeping into the drainage ditch immediately downgradient from MW-112. The locations of these LNAPL observations indicate that the source of the mobile LNAPL was likely the western UST location. The thickness of the mobile LNAPL layers observed in well MW-112 during the 1980s is not known. The migration pathway between the former USTs and the drainage ditch is indicated by the distribution of BTEX in soils depicted on Figure 5.3. Law (1994) reported the presence (in 1994) of a slight petroleum sheen on water in the southern drainage ditch near the corrugated steel observation wells installed in 1983. A slight sheen was observed in the southern ditch near well MW-113 in 1995. However, mobile LNAPL was not observed in any of the monitoring wells at the site in 1995.

### **5.5.2 Shallow Dissolved Contamination**

Shallow groundwater contamination was detected at the MOGAS site in December 1988 during the initial Stage 1 remedial investigation performed by ERM (1990). Groundwater samples from three wells (MW-111, MW-112, and MW-113) were analyzed for total dissolved solids (TDS), total and dissolved lead, TPH, aromatic VOCs, and ethylene dibromide (EDB). Except for the BTEX compounds, none of the COPCs identified in Section 4 were targeted for analysis. Federal MCL drinking water standards for benzene, ethylbenzene, and toluene were exceeded at well MW-112 in 1988. Maximum detected concentrations of these compounds were 14,000 µg/L, 5,100 µg/L, and 34,000 µg/L, respectively. Except for a detection of benzene at 15 µg/L in well MW-113, BTEX compounds were not detected at the other wells sampled in 1988.

Ten groundwater samples were collected from the MOGAS area in June 1993 and screened in the field for BTEX and total FID VOCs (Law, 1993). In addition, three samples were analyzed for BTEX at a fixed-base laboratory to confirm field screening results. The COPCs chlorobenzene, naphthalene, and the TMB compounds were not targeted for analysis during this sampling event. The sampling results further defined the upgradient and crossgradient extent of dissolved hydrocarbon contamination. Figures and tables depicting the 1993 sampling results are contained in Appendix A. The highest BTEX concentration (1,920 µg/L) was detected immediately south of the eastern UST location. Benzene concentrations exceeded federal MCLs in six samples. The sampling results indicated that BTEX concentrations decreased rapidly to the north, east, and west of the UST locations, confirming that the former USTs are the primary contamination source.

Five additional monitoring wells (MW-01 through MW-05) were installed at the MOGAS site in March 1994 by Law (1994). The well locations were selected based on the results of previous investigations. Groundwater samples from the five new and the three previously installed wells were collected in April 1994, and analyzed for aromatic VOCs and total lead. Three of the groundwater COPCs identified in Section 4, including the two TMB compounds and naphthalene, were not targeted for analysis. Similar to the ERM (1990) investigation performed in 1988, the highest dissolved contaminant concentrations were detected in the sample from MW-112, located downgradient from the western UST location.

During the Phase I RBCA investigation in January 1995, 13 temporary groundwater monitoring points were installed, and 16 groundwater samples were collected from 7 of the monitoring points, one SVE pilot test well, and the 8 previously installed monitoring wells. The only petroleum-related constituents targeted for analysis during the Phase I sampling program were BTEX, TMBs, TEMBs, and total fuel carbon. Therefore, data for the remaining groundwater COPC identified in Section 4 (naphthalene) were not obtained. The Phase I samples also were analyzed for a suite of parameters designed to facilitate an intrinsic remediation analysis (see Table 2.2).

The dissolved BTEX results for Phase I groundwater samples are shown on Figure 5.9. The distribution of detected BTEX compounds suggests the presence of two overlapping plumes emanating from the eastern and western UST locations. The maximum dissolved BTEX concentrations in the eastern and western plumes were 16,102 µg/L and 45,170 µg/L at monitoring point MOC-05 and monitoring well MW-112, respectively. Both plumes appear to be moving directly toward the southern drainage ditch. The relatively low concentration of dissolved BTEX detected south of the ditch at well MW-04 (10.6 µg/L) indicates that the majority of the contaminated groundwater is discharging to the ditch. The distributions of the TMB compounds detected in Phase I groundwater samples are similar to that shown for BTEX on Figure 5.9.

During Phase II of the RBCA investigation, which was performed in August and September 1995, a total of 37 groundwater samples were collected from the 2 Phase II air sparging wells, 13 Phase I temporary monitoring points, the 8 previously installed monitoring wells, and 14 new monitoring wells installed during Phase II. The samples

were analyzed for aromatic VOCs, SVOCs, and a suite of geochemical indicator parameters designed to support an intrinsic remediation evaluation for groundwater at the site. Each of the COPCs identified in Section 4 was targeted for analysis during this sampling event.

The distributions of dissolved BTEX and benzene in Phase II groundwater samples are shown on Figures 5.10 and 5.11, respectively. The distribution and magnitude of detected BTEX concentrations in August/September 1995 are very similar to the Phase I January 1995 sampling event (Figure 5.9). For example, the maximum Phase II BTEX concentration in the plume emanating from the western UST location in August/September was 47,300  $\mu\text{g/L}$  (at well MW-112), compared to 45,170  $\mu\text{g/L}$  in January. Similarly, the maximum Phase II concentration in the eastern plume was 12,150  $\mu\text{g/L}$  at monitoring point MOC-05, compared to 16,102  $\mu\text{g/L}$  in January. The relatively low BTEX concentration detected immediately adjacent to and downgradient from the western UST location at monitoring point MOC-10 suggests that the core of the western plume is located further south in the vicinity of MW-112 rather than at the western UST location. This shifting of the plume core may be due to the excavation of contaminated soils that occurred upgradient from MOC-10 during removal of the USTs in 1993, whereas grossly-contaminated soils in the LNAPL smear zone south of MOC-10 are more prevalent.

It should be noted that the 3-foot-long screens of the Phase I monitoring points, including MOC-10, begin at depths of 10 to 12 feet bgs, whereas the water table beneath the asphalt in the immediate vicinity of the former USTs is generally approximately 9 feet bgs. Closer to the southern drainage ditch the water table is more shallow. Therefore, the monitoring points are not screened across the groundwater surface, and samples from these points are probably not indicative of maximum dissolved BTEX concentrations. The same observation is true for the air sparging pilot test wells (AS-01 and AS-02), which have screened intervals similar to those of the monitoring points. This observation explains the relatively low magnitude of the BTEX detections at some of these locations relative to nearby, higher detections in monitoring wells screened across the water table. Monitoring point MOV-01-03 is screened across the water table. The relationship between screen depth and dissolved BTEX concentration also indicates that concentrations decrease rapidly with depth in the shallow groundwater zone.

The detection of 34.7  $\mu\text{g/L}$  BTEX in upgradient well MW-10 (Figure 5.10) indicates the presence of a secondary, relatively minor contaminant source north of the former UST locations. Similar to Phase I data, the Phase II dissolved BTEX data indicate that the majority of contaminated groundwater is discharging to the southern drainage ditch. However, the detection of 126  $\mu\text{g/L}$  BTEX at well MW-04, located approximately 25 feet south of the ditch, suggests that some underflow of contaminated groundwater may be occurring. Dissolved BTEX was not detected in MW-12, MW-15, MW-16, and MW-18, all of which are screened in the deep groundwater zone. The horizontal and vertical distributions of dissolved benzene in shallow groundwater (Figure 5.11) is similar to that shown for BTEX in Figure 5.10.

The combined distributions of 1,2,4-TMB and 1,3,5-TMB in Phase II groundwater samples is shown on Figure 5.12. As shown on these figures, the magnitudes of the detected concentrations of these compounds are substantially lower than those of the BTEX compounds, but the lateral distributions are very similar. The USEPA Region III (1996) direct-contact RBSL for the TMB compounds in groundwater is 300 µg/L (Table 4.9). Concentrations of both TMBs exceeded this comparison criterion at well MW-112 and monitoring point MOV-01-03 (sampled in January 1995), located downgradient from the western UST location. The only exceedence of this RBSL downgradient from the eastern UST location was at MOC-05, where 1,2,4-TMB was detected at a concentration of 510 µg/L. The TMBs were not detected in groundwater from deep monitoring wells MW-12, MW-15, MW-16, and MW-18.

The distribution of the SVOC naphthalene in Phase II groundwater samples is shown on Figure 5.13. Naphthalene was detected in only two samples (MW-112 and MOC-10), both located downgradient from the western UST location. Therefore, the lateral extent of significantly elevated concentrations of this compound appears to be relatively limited. The detected concentrations at both locations exceeded the SCDHEC direct-contact RBSL for naphthalene of 25 µg/L, but the USEPA RBSL of 1,500 µg/L was not exceeded.

### 5.5.3 Surface Water and Sediment Quality

Benzene is the only analyte retained as a surface water COPC during the Tier 1 screening presented in Section 4. The SCDHEC (1995) human health surface water RBSL for benzene is 5 µg/L (Table 4.11). RBSLs for sediment are not available. No available aquatic life comparison criteria were exceeded in drainage ditch surface water (Section 4).

ERM (1990) collected two surface water samples (SW-5 and SW-6) from the southern drainage ditch in December 1988 and analyzed them for aromatic VOCs. The sampling station locations are shown on Figure 1.4, and analytical results are contained in Appendix A. Benzene was not detected at the upstream sampling station, located approximately 90 feet east of well MW-113 (Figure 5.12). This station is located upstream from the contaminated groundwater discharge area. Benzene was detected at a concentration of 2 µg/L at the downstream sampling location just upstream from the culvert beneath Third Street.

Law (1994) collected four surface water and sediment samples from the southern drainage ditch in April 1994 and analyzed them for BTEX, methyl tert-butyl ether (MTBE), and total lead to determine if site activities had impacted the ditch. The sampling locations are shown on Figure 1.4, and analytical data are contained in Appendix A. Benzene was detected directly south of both the eastern and western UST locations at concentrations of 15 µg/L and 16 µg/L, respectively. Benzene also was detected at the furthest downstream station, SW-04, at a concentration of 14 µg/L. This station also is located within the estimated contaminated groundwater discharge area.

Parsons ES collected surface water samples in the drainage ditch west of Third Street during the January 1995 investigation of the POL Bulk Fuel Storage Area (Parsons ES, 1995). One sample was collected immediately west of Third Street, downstream from the MOGAS site but upstream from the portion of the ditch affected by discharge of contaminated groundwater migrating from the POL fuel storage tanks (Figure 5.14). The BTEX and benzene concentrations detected in this sample were 93.4 µg/L and 19.8 µg/L, respectively, indicating that contamination originating from the MOGAS site was persistent west of Third Avenue at the time of this sampling event. Approximately 550 feet further downstream from (west of) this sampling location, however, the total BTEX concentration in surface water was reduced to 1 µg/L, and benzene was not detected.

Four surface water and sediment samples were collected by Parsons ES in September 1995 and analyzed for aromatic VOCs and TOC. As shown on Figure 5.14, the maximum benzene concentrations in surface water and sediment were detected at SW/SD-03, located directly south of the eastern UST area. Lower, but still elevated, benzene concentrations also were detected at SW/SD-02, south of the western UST location. However, benzene was not detected in surface water or sediment at the downstream site boundary near Third Street, indicating that concentrations were being rapidly reduced through natural attenuation processes (i.e., dilution, volatilization, biodegradation, and sorption).

## 5.6 SUMMARY

Soil contamination at the MOGAS site is predominantly located near the water table at and downgradient from the former UST locations. The soil quality data indicate that mobile LNAPL migrated from the western UST location to the southern drainage ditch, leaving a trail of residual LNAPL that is a continuing source of dissolved groundwater contamination. Residual LNAPL also is present downgradient from the eastern UST location; however, the southern extent of the LNAPL in this area is not well defined. Significant soil contamination does not appear to be present south of the drainage ditch. The contaminants identified as soil COPCs all exceeded the Tier 1 RBSL for leaching (Table 4.8); none exceeded a health-protective direct-contact Tier 1 RBSL derived for an industrial/commercial scenario (Tables 4.6 and 4.7). The average concentrations of contaminants detected in vadose zone soils are lower than average concentrations calculated using soil data from both above and below the water table. The long-term impacts of soil contamination on underlying groundwater at this site, accounting for site-specific conditions, is quantitatively considered in Section 6 of this CAP.

Several fuel-related compounds (benzene, toluene, ethylbenzene, xylenes, naphthalene, 1,2,4-TMB, and 1,3,5-TMB) were identified as groundwater COPCs for the MOGAS site. Significant dissolved contamination appears to be limited to the immediate vicinity of the former USTs and the area between the former USTs and the drainage ditch. In addition, dissolved analyte concentrations appear to decrease significantly with depth in the shallow groundwater zone, with the greatest mass of dissolved contaminants being present in the uppermost 5 feet of this zone. COPCs were not detected in the wells screened in the deep groundwater zone. Nearly all of the dissolved contamination in the shallow groundwater zone appears to discharge to the

southern drainage ditch, as evidenced by the detection of contamination in ditch surface water and sediment, and the relative lack of contamination in groundwater south of the ditch. However, some relatively minor underflow of dissolved contaminants beneath the ditch may be occurring. The degree to which discharge to the ditch occurs may be seasonally variable. Data from two sampling events indicated that benzene concentrations in surface water were eliminated or significantly reduced by the downstream site boundary near Third Street. However, data from a third (January 1995) sampling event indicated that more elevated benzene concentrations were present in surface water immediately west of Third Street. Detected benzene concentrations do exceed the SCDHEC (1995) human health RBSL for surface water (Table 4.11 and Figure 5.14). No aquatic life criteria for surface water were exceeded, and sediment RBSLs are not available.

The effects of the chemical characteristics and site-specific characteristics of each of the groundwater COPCs on their fate and transport within the shallow groundwater zone and in the drainage ditch are examined in Section 6. Emphasis is placed on documenting the effects of natural physical, chemical, and biological processes on COPC mass, concentration, persistence, toxicity, and mobility.

## SECTION 6

### TIER 2 QUANTITATIVE CHEMICAL FATE ASSESSMENT

#### 6.1 INTRODUCTION

As discussed in Section 1, the primary objective of this CAP is to develop and describe a risk-based corrective action for the MOGAS site that meets the requirements of SCDHEC (1995). The draft CAP prepared by Law (1994) recommended installation of a combined SVE/*in situ* air sparging system to treat both the contaminated soil and groundwater at the MOGAS site. This CAP supplements the recommendations set forth in the draft CAP prepared by Law (1994). This section specifically documents the potential for natural chemical attenuation processes (alone and possibly in combination with source reduction technologies such as SVE, bioventing, and air sparging) to reduce the persistence, mobility, mass, and toxicity of COPCs in soil vapor, soil, groundwater, and surface water at the MOGAS site. The quantitative chemical fate assessment presented in this section was completed to support derivation of Tier 2 SSTLs, including an estimate of the compliance period required to reduce COPCs to concentrations below matrix-specific SSTLs and eventually RBSLs.

As discussed in Section 4, maximum detected concentrations of each of the BTEX compounds in soil gas exceeded both the SCDHEC (1995) and USEPA Region III (1996) inhalation RBSLs. Direct-contact RBSLs were not exceeded by detected soil concentrations, but average concentrations (computed using data from both above and below the water table) of five compounds (benzene, toluene, ethylbenzene, chlorobenzene, 1,3,5-TMB, and naphthalene) exceeded SCDHEC and/or USEPA Region III leachability RBSLs. Average vadose zone concentrations of ethylbenzene and chlorobenzene did not exceed SCDHEC or USEPA leachability RBSLs. The maximum concentrations of seven analytes in groundwater exceeded SCDHEC and/or EPA direct-contact RBSLs. These seven analytes included the BTEX compounds, naphthalene, 1,2,4-TMB, and 1,3,5-TMB. The only analyte found to exceed the SCDHEC human health surface water RBSL was benzene. No available surface water comparison criteria for protection of aquatic organisms were exceeded, and no sediment RBSLs are available.

#### 6.2 OPERATIVE MECHANISMS OF CONTAMINANT ATTENUATION

Understanding the fate of COPCs in environmental media is critical to evaluating and predicting contaminant distribution patterns. There are several physical, chemical, and biological processes that influence how a chemical behaves in soil gas, soil, and groundwater. The following paragraphs present a brief overview of the major chemical characteristics that control the fate of the COPCs in soil gas, soil, and groundwater at

the MOGAS site. These chemical characteristics ultimately determine if the mass of contaminants in the environment can be substantially eliminated or rendered immobile by natural processes. The positive effects of these natural processes on reducing the mass of COPC compounds and/or minimizing the extent of COPC migration in environmental media such as groundwater and surface water has been termed intrinsic remediation.

### **6.2.1 Chemical Characteristics and Mass Transport Mechanisms**

The relative solubility, sorptive nature, and volatility of a chemical can govern the effectiveness of nondestructive chemical processes that may prohibit significant contaminant migration, but may not result in a permanent reduction in contaminant mass. Examples of nondestructive attenuation processes include volatilization, sorption, advection, and dispersion. These processes must be evaluated when determining whether a compound poses, or has the potential to pose, a risk to human health or the environment. If the contaminant is not likely to reach a potential receptor, the exposure pathway is incomplete and the contaminant poses no risk.

#### **6.2.1.1 Solubility**

The water solubility of a chemical species defines how that particular chemical can partition (leach) from a contaminant source and dissolve into and migrate with groundwater. The BTEX and TMB compounds and chlorobenzene are slightly to moderately water soluble, with measured solubilities ranging from more than 1,700 mg/L for benzene to less than 75 mg/L for TMBs (Bohon and Claussen, 1951; Mackay and Shiu, 1981; Verschueren, 1983; Isnard and Lambert, 1988; Howard, 1990). The solubility of naphthalene is relatively low (approximately 30 mg/L at 25°C) (Verschueren, 1983). Consequently, even though more soluble compounds such as benzene may make up a low mass fraction of the initial source of contamination, they should preferentially leach from LNAPL (mobile or residual) into groundwater and migrate as dissolved contamination (Lyman *et al.*, 1992). In contrast, TMBs, chlorobenzene, and naphthalene are expected to leach at a slower rate even though these compounds may originally account for a higher mass fraction than benzene in the LNAPL. The leaching rates of the remaining BTEX compounds, having solubilities between 145 and 500 mg/L, are expected to be between the rates for benzene and the TMBs.

The difference in solubility between BTEX compounds and other, less soluble, fuel hydrocarbons is the cause of the disproportionate effect that BTEX can have on groundwater quality in comparison to other hydrocarbons commonly found in automotive and aviation fuels. For instance, automotive gasoline may consist of more than 30 percent of BTEX compounds by weight (Metcalf & Eddy, 1993); however, the BTEX compounds can account for at least 80 percent of the total hydrocarbons dissolved in groundwater (ES, 1993a).

#### 6.2.1.2 Sorptive Properties

Another chemical characteristic that can govern how a compound is attenuated in soil gas, soil, and groundwater is its sorptive properties. If a contaminant can be strongly sorbed to the aquifer matrix, the compound will be less mobile and less likely to be transported great distances from the source area. The BTEX compounds are less sorptive than most other petroleum hydrocarbons. Benzene does not sorb readily to soil and is considered the most mobile of the BTEX compounds. Toluene sorbs more readily to soil than benzene, but is still very mobile. Ethylbenzene sorbs more strongly to soil than benzene but less strongly than toluene. Of all the BTEX compounds, xylenes sorb most strongly to soil, but can still leach from unsaturated soil and dissolve into and migrate slowly in groundwater (Abdul *et al.*, 1987). Chlorobenzene also would be expected to percolate into and migrate with groundwater in sandy soils having a low organic carbon content. In comparison, heavier hydrocarbons such as TMB compounds and naphthalene sorb more strongly to the soil matrix and migration is limited both in soil and in groundwater (Verschuieren, 1983).

The organic carbon content of unsaturated and saturated soils at the MOGAS site was measured as part of the Phase II 1995 sampling event. The TOC content ranged from less than 0.06 percent to 1.34 percent, with an average value of 0.06 percent. The BTEX compounds sorb to that portion of the soil matrix that is composed of organic carbon and/or fine clay particles. Thus, an average of 0.0006 kg of organic carbon per kilogram of soil is available to sorb contaminants. This level of organic carbon is not likely to significantly retard chemical migration in groundwater. For soils containing less than 0.1 percent organic carbon, the silt and clay fraction of the soil may dominate the sorption process (Mehran *et al.*, 1987). The relatively uniform, fine- to medium-grained sands found in the shallow groundwater zone at this site contain a very small silt/clay fraction, which also should minimize contaminant sorption. The effect of sorption on solute transport velocities in groundwater is described in subsequent sections.

#### 6.2.1.3 Volatility

The volatility of each of the COPC compounds also can affect how they behave in the environment. Except for naphthalene, all of the COPC compounds are classified as volatile chemicals because they have vapor pressures in excess of 0.1 millimeter of mercury (mm Hg). Benzene is the most volatile, with a vapor pressure of about 95 mm Hg. Chlorobenzene, toluene, ethylbenzene, and xylenes have intermediate volatilities, with vapor pressures ranging from 7 to 22 mm Hg. The TMB compounds are substantially less volatile, with vapor pressures between 1 and 2 mm Hg. Naphthalene is the least volatile of the COPCs, with a vapor pressure of 0.13 mm Hg.

Volatilization was not directly investigated as a mass transport mechanism at the MOGAS site. The asphalt cap overlying the former UST locations should minimize the importance of this process in this portion of the site. However, in the grassy area near the southern drainage ditch, VOC emissions to the atmosphere may be more significant. Because of the substantial concentrations of COPCs detected in soil gas (Table 4.9), and because ambient air sampling data for these COPCs are not available,

the volatilization pathway was retained as a potentially completed pathway for human receptors. However, the approximately 100-day-long SVE pilot test performed at the site from November 1995 through January 1996 has removed a portion of the volatile COPC mass from the subsurface, which should lessen the significance of this pathway.

#### **6.2.1.4 Aquatic Fate**

The following paragraphs summarize physical, chemical, and biological processes that could affect COPCs following their discharge to the southern drainage ditch.

Volatilization is an important process promoting the removal of the BTEX compounds from surface water. Benzene, toluene, and ethylbenzene also are susceptible to biodegradation, while photodegradation may be a significant benzene removal process in surface water for that residual mass that is not conducive to microbial degradation. Benzene and toluene are not expected to significantly adsorb to sediment; the adsorption potential of ethylbenzene and xylenes is slight to moderate.

Volatilization, photodegradation, sorption (to suspended solids and sediments), and biodegradation are the primary removal mechanisms for naphthalene in surface water. The actual predominant mechanisms change with variations in several factors, such as water flow rate, quantity and nature of sediments and suspended particles, and water clarity.

The primary removal mechanism for chlorobenzene in surface water will be volatilization. Secondary removal processes include biodegradation (which increases in significance with increasing water temperature and decreasing salinity), and photolysis, which occurs at a relatively slow rate. The tendency for chlorobenzene to adsorb to soils and sediments in surface water is slight to moderate.

In addition to the processes described above, the COPCs will be diluted following their discharge to surface water. Dilution will be most effective during significant precipitation events, which have the potential to cause slow-moving, long-residence-time water to be mixed with substantial volumes of fresh water and flushed downstream.

#### **6.2.1.5 Discussion**

The preceding discussion shows that there are several important chemical properties to consider when assessing whether COPC contamination at the MOGAS site may present an unacceptable risk to human health or the environment. Site contaminants characterized by high water solubility and low sorptive properties can be rapidly introduced into and transported with groundwater. Less soluble and more sorptive compounds are likely to be persistent in source area soils. Consequently, benzene, as one of the most toxic, most soluble, and least sorptive COPCs, is expected to drive the type and magnitude of remediation necessary to isolate the contamination and protect downgradient receptors. In addition, benzene was identified as a COPC in all evaluated media (soil, groundwater, surface water, and air).

The nature and extent of COPC contamination at the MOGAS site as defined to date can be explained in part based on the solubility and sorptive properties of the various compounds. For example, although benzene was the only BTEX constituent detected in surface water at the site, measured benzene concentrations in the four relatively contaminated soil samples collected at SVE wells VENT-01 and VENT-02 were all lower than the measured concentrations of toluene, ethylbenzene, and xylenes at these sampling locations. These observations indicate that benzene is the BTEX constituent most likely to leach from soils, dissolve into groundwater, and migrate to the ditch.

Figures 5.10 through 5.12 illustrate the August-September 1995 distributions of dissolved BTEX, benzene, and TMBs, respectively, in groundwater. The individual lateral distributions of toluene, ethylbenzene, and xylenes in groundwater are all similar to the distributions shown in these figures. Because the distance between the former UST locations and the southern ditch is only approximately 100 feet, each of these compounds has had ample time to migrate to the ditch. Therefore, differences in the migration characteristics of the BTEX and TMB compounds caused by variations in volatility, sorptive properties, and solubility are not readily apparent.

The distribution of naphthalene in groundwater is shown on Figure 5.13. The magnitude and lateral extent of this compound, which has a relatively low solubility in groundwater, appears to be small relative to the BTEX compounds. Therefore, while it can be transported within sandy aquifers, it does not readily dissolve from residual LNAPL. Its low solubility may be a primary cause for the limited presence of this compound in the groundwater system beneath the site. Naphthalene was detected in five of the nine soil samples collected and analyzed for this compound in 1995, with a maximum concentration of 24,000  $\mu\text{g/kg}$ .

The effectiveness of the contaminant dilution and removal processes operating in the drainage ditch, described in Section 6.2.1.4, are evidenced by the fact that benzene is the only surface water COPC retained following the Tier 1 evaluation in Section 4. In addition, benzene concentrations in surface water have been observed to decrease to very low or below detection levels with distance in the downstream direction, indicating that concentrations in surface water are being diminished by a combination of dilution, volatilization, and biodegradation. Benzene was detected in two sediment samples at concentrations of 2,700  $\mu\text{g/kg}$  (SD-02) and 6,300  $\mu\text{g/kg}$  (SD-03). Benzene was not detected in sediment at the furthest upstream and downstream sampling stations (SD-04 and SD-01, respectively) (Figure 5.14).

### 6.2.2 Biodegradation of COPCs

Biodegradation also may act as a chemical attenuation process in soil and groundwater. In comparison to nondestructive chemical attenuation processes, destructive chemical attenuation processes result in the permanent removal of contaminant mass from the environment and may reduce the length of time required to attain site-specific cleanup goals. Documenting and distinguishing the effects of destructive attenuation processes, such as biodegradation, from nondestructive attenuation processes is important in evaluating the potential for intrinsic remediation to bring about a continuous reduction in contaminant mass over time. The effectiveness

of destructive attenuation processes at reducing contaminant mass at a site depends on how susceptible the chemical is to biodegradation and whether the site is characterized by physical, chemical, and biological conditions favorable to such processes.

Numerous laboratory and field studies have shown that hydrocarbon-degrading bacteria can participate in the degradation of many of the chemical components of fuels under both aerobic and anaerobic conditions (e.g., Jobson *et al.*, 1972; Perry, 1977; Atlas, 1981, 1984, 1988; Gibson, 1984; Reinhard *et al.*, 1984; Young, 1984; Bartha, 1986; Wilson *et al.*, 1986, 1987, 1990; Baedecker *et al.*, 1988; Lee, 1988; Chiang *et al.*, 1989; Grbic-Galic, 1989, 1990; Leahy and Colwell, 1990; Parker *et al.*, 1990; Stieber *et al.*, 1990; Altenschmidt and Fuchs, 1991; Alvarez and Vogel, 1991; Baedecker and Cozzarelli, 1991; Bauman, 1991; Borden, 1991; Brown and McFarland, 1991; Haag *et al.*, 1991; Hutchins and Wilson, 1991; Beller *et al.*, 1992; Bouwer, 1992; Edwards and Grbic-Galic, 1992; Thierrin *et al.*, 1992; Malone *et al.*, 1993; Davis *et al.*, 1994). The biodegradation of BTEX is particularly well documented. Biodegradation of fuel hydrocarbons will occur when an indigenous population of hydrocarbon-degrading microorganisms is present in the soil and groundwater, and sufficient concentrations of electron acceptors and nutrients, including fuel hydrocarbons, are available to these organisms. Soil and groundwater with a history of exposure to fuel hydrocarbons generally contain microbial populations competent to facilitate biodegradation reactions (Zobell, 1946; Litchfield and Clark, 1973; Borden, 1994; Seech *et al.*, 1994; Simpkin and Giesbrecht, 1994). The chemical basis for the biodegradation of BTEX compounds is described in more detail in Section 6.4, where geochemical data relevant to documenting biodegradation at the field scale at the MOGAS site are presented.

Chlorobenzene biodegrades more slowly than BTEX in sandy aquifers such as the shallow aquifer at the MOGAS site (Chapelle, 1993). If biodegradation does occur, end products include 2-chlorophenol and/or 4-chlorophenol, among others. Biodegradation rates for naphthalene are enhanced with higher concentrations of both DO and anthropogenic organic carbon (i.e., petroleum contaminants) that can act as an electron donor. Biodegradation of naphthalene is slower under anaerobic groundwater conditions.

### **6.3 EVIDENCE OF CONTAMINANT BIODEGRADATION OVER TIME AND DISTANCE**

The first step in determining whether site data indicate that COPCs are biodegrading in soils and groundwater at the MOGAS site was to compare analytical data on the magnitude and extent of site contamination collected during previous investigations (ERM, 1990; Law, 1994) to similar data collected in January and August-September 1995 pursuant to CAP preparation. The purpose of this comparison was to assess the evidence of field-scale contaminant mass loss. Changes in the concentrations and extent of contamination at a site over time that cannot be explained by physical processes (e.g., leaching, transport in groundwater) may be an indication that contaminants are biodegrading at the site.

The BTEX compounds are the analytes for which the largest historical database is available. The TMBs were targeted for analysis only during the two 1995 sampling events, and therefore only limited comparisons can be made. The historical database for naphthalene and chlorobenzene is inadequate for analysis of temporal trends.

#### **6.3.1 Evidence of COPC Leaching from Soils**

At the MOGAS site, soil COPCs that exceeded Tier 1 RBSLs identified by SCDHEC and/or USEPA Region III include benzene, toluene, ethylbenzene, naphthalene, chlorobenzene, and 1,3,5-TMB (Table 4.8). If only vadose zone soils are considered, then soil COPCs include benzene, toluene, naphthalene, and 1,3,5-TMB. The widespread presence of substantial concentrations of the BTEX compounds in soils bordering the water table has been demonstrated in this and previous investigations. Soil quality data collected in 1995 also demonstrated the presence of chlorobenzene, naphthalene, and 1,3,5-TMB in the soil column near and downgradient from the former UST locations. The presence of these compounds in groundwater at the MOGAS site indicates that they are being leached from soils. Water table fluctuation or rainwater infiltration could be release mechanisms for soluble organics that are sorbed to vadose zone or capillary fringe soils within the source area. In addition, substantial soil contamination is present beneath the average water table as a result of mobile LNAPL migration from the former UST locations toward the southern drainage ditch. The degree to which these chemicals could partition from source area soils and leach into underlying groundwater depends on solubility and sorptive characteristics of the chemicals, soil characteristics, and the amount of water that passes through the soil column. As discussed previously, each of the soil COPCs can dissolve into and migrate with groundwater.

#### **6.3.2 Observed Contaminant Loss from Groundwater**

Historical variations in dissolved BTEX concentrations in individual monitoring wells and points were assessed to determine whether concentrations were decreasing through time due to the effects of biodegradation and removal of the USTs. The data suggest that such a decrease is occurring; however, a clear, consistent trend of decreasing concentrations through time is not evident.

Temporal variations in dissolved BTEX concentrations in eight monitoring wells/points are illustrated in Figures 6.1 and 6.2. BTEX concentrations in four monitoring points that are upgradient to slightly cross-gradient from the former UST locations (MOC-03, MOC-04, MOC-08, and MOC-11) decreased by an average of 91 percent between the January and August-September 1995 sampling events, suggesting that the contaminant mass near the edges of the plume in these areas is decreasing. The observed decrease in contaminant concentrations may also be due in part to the dilutional effect of summer rainfall. Similarly, total BTEX concentrations in a fifth monitoring point (MOC-05), located directly downgradient from the eastern UST location, decreased by 25 percent between the January and August-September 1995 sampling events. BTEX concentrations at well MW-02 were relatively stable between April 1994 and January 1995, and exhibited a nearly three-fold increase from January to August 1995. The reason for this increase is not known, but may be related to natural seasonal variations in contaminant concentrations and/or variations in sample-specific collection and handling techniques. BTEX concentrations in wells MW-112

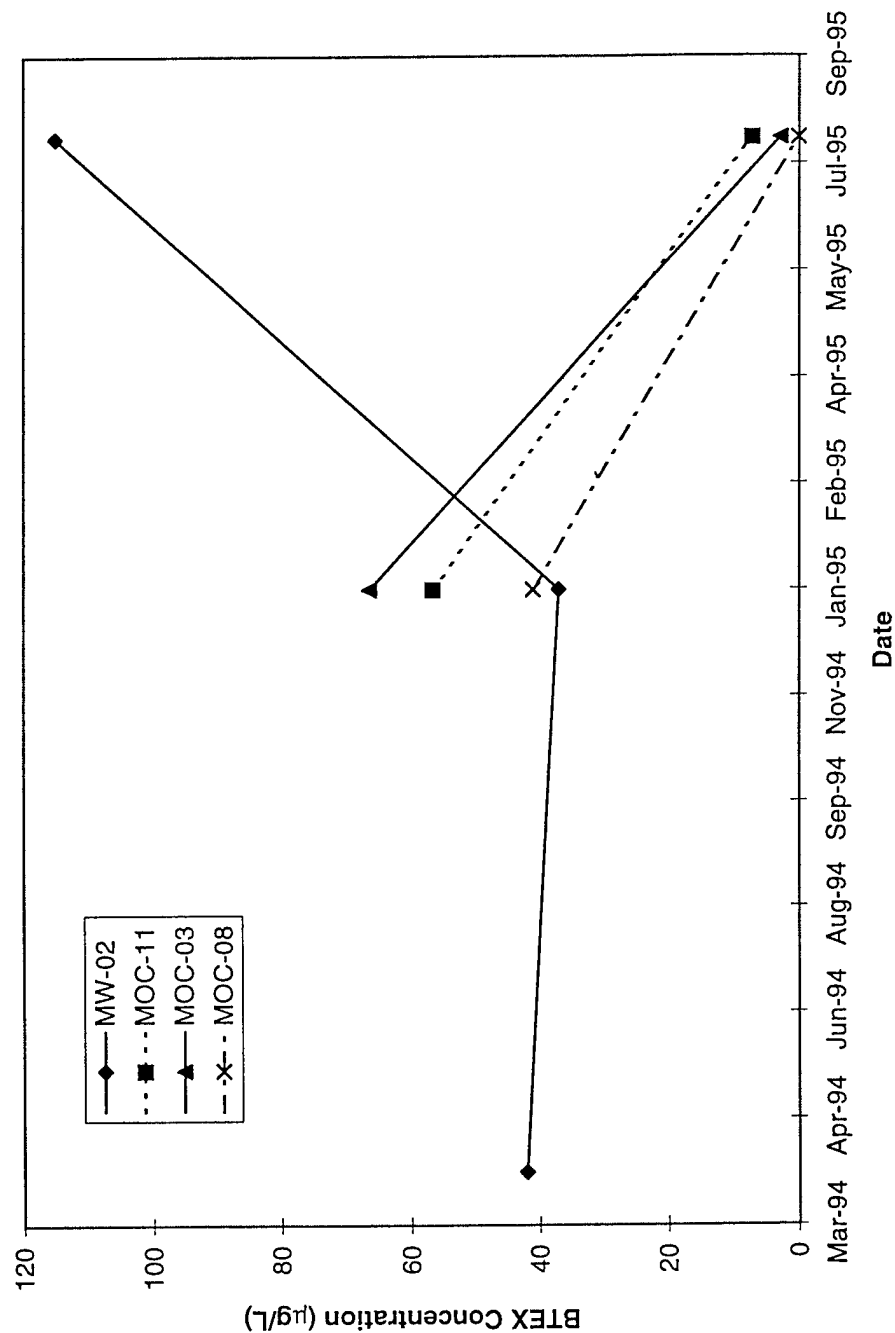


FIGURE 6.1  
HISTORICAL VARIATION IN  
DISSOLVED BTEX CONCENTRATIONS  
(WELLS/POINTS MW-02, MW-03,  
MOC-08, AND MOC-11)  
MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**  
Denver, Colorado

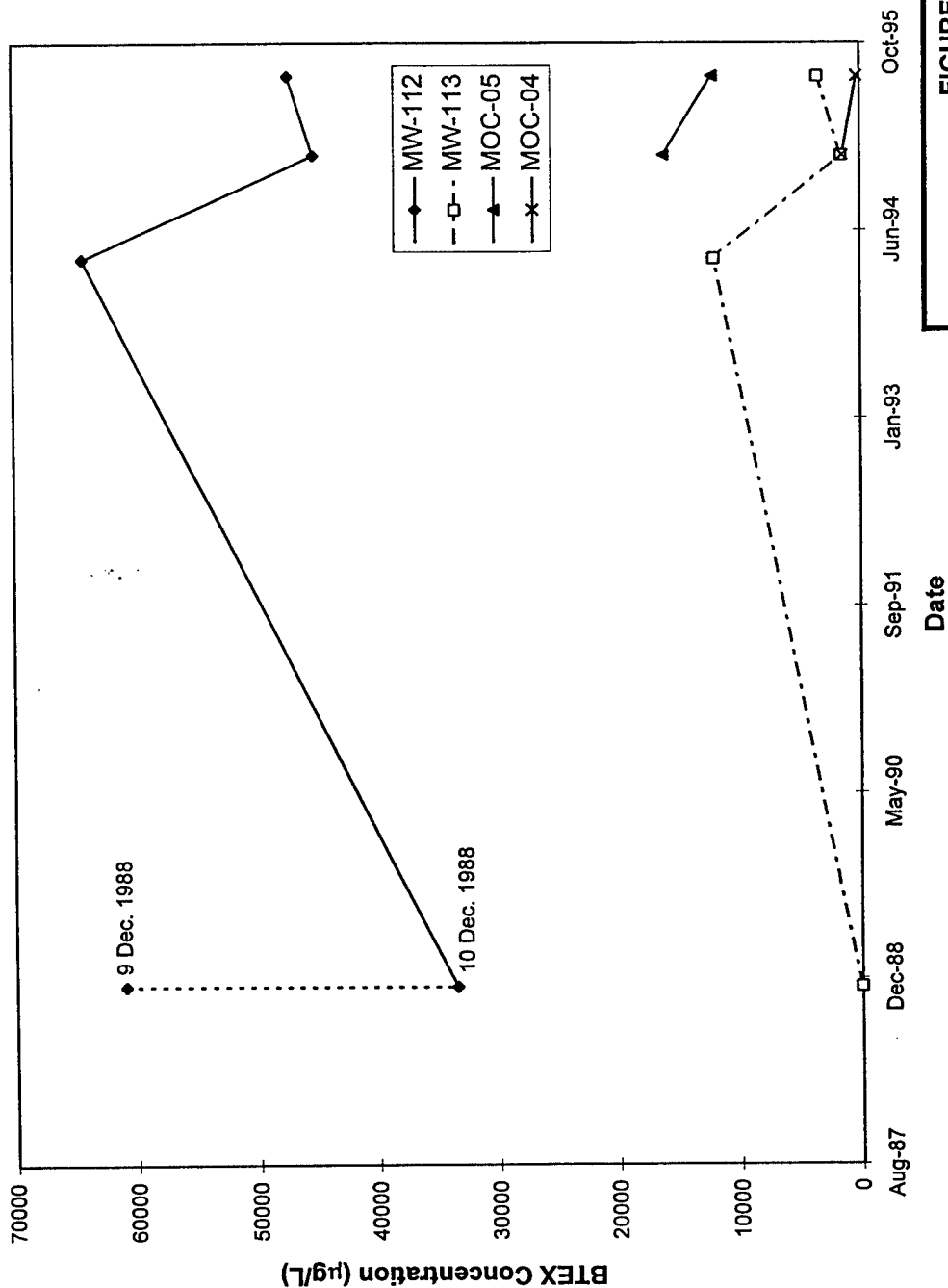


FIGURE 6.2

# **HISTORICAL VARIATION IN DISSOLVED BTEX CONCENTRATIONS (WELLS/POINTS MW-112, MW-113, MOC-04, AND MOC-05)**

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**  
Denver, Colorado

and MW-113 have varied in a relatively erratic fashion; however, the BTEX concentrations detected at these wells in 1995 were substantially lower than the 1994 concentrations. In December 1988, well MW-112 was sampled twice on consecutive days. The dissolved BTEX concentrations in the first and second samples were 61,000 µg/L and 33,500 µg/L, respectively (ERM, 1990). The temporal variations in concentration exhibited by each of the individual BTEX compounds are generally similar to those portrayed for BTEX on Figures 6.1 and 6.2.

In summary, the data suggest that dissolved BTEX concentrations have generally decreased from 1994 to 1995. However, significant concentration decreases between the two 1995 sampling events are not evident.

### 6.3.3 Estimating Site-Specific Contaminant Biodegradation Rates

It is important to distinguish between the effects of nondestructive attenuation processes (e.g., advection, dispersion, and sorption) and the effects of destructive attenuation processes (i.e., biodegradation) on the mass of dissolved contaminants in the groundwater at the MOGAS site. Comparison of analytical data from several sampling events suggests that at least some of the groundwater COPCs are being removed from saturated soils and groundwater by destructive mechanisms. In addition, available geochemical data discussed later in this section suggest that anaerobic degradation is occurring in the vicinity of the MOGAS site. The inclusion of degradation rates in fate and transport models is therefore desirable to make solute transport predictions that are meaningful. As with a large number of biological processes, biodegradation rates can generally be described using a first-order rate constant (Chapelle, 1993). The solution to the first-order decay is:

$$\frac{C}{C_0} = e^{-kt}$$

where: C = Contaminant Concentration at Time t,  
C<sub>0</sub> = Initial Contaminant Concentration,  
k = Coefficient of Anaerobic Decay (anaerobic rate constant), and  
t = Time.

To quantify these effects, an exponential regression method can be used to derive degradation rates from concentration reduction data versus time (Buscheck and Alcantar, 1996). The reduction in COPC concentrations at specific sampling points and the reduction in site average COPC concentrations can be used to estimate a first-order attenuation rate, provided the plume size is relatively stable or decreasing. A description of the rate estimation method is included in Appendix F.

This method requires that groundwater analytical data for a minimum of two sampling stations (preferably at least three) are available. To the extent possible, the stations should be located within the plume along a line parallel to groundwater flow and contaminant migration, preferably along the longitudinal axis of the plume. In addition, the stations should be far enough apart that significant contaminant

concentration changes due to the effects of biodegradation are evidenced from one station to the next.

Unfortunately, the conditions described in the preceding paragraph are not fulfilled at the MOGAS site. The highest contaminant and tracer concentrations were detected downgradient from the former UST locations near the drainage ditch and the toe of the BTEX plume. However, the POL Bulk Fuel Storage Area, which is hydrogeologically similar to the MOGAS site, is located immediately west of the MOGAS site across Third Street (Figure 1.3). A biodegradation rate constant for BTEX of  $0.0021 \text{ day}^{-1}$  computed for the POL site was used for predictive purposes in the calibrated numerical fate and transport model constructed for that site (Parsons ES, 1995). As described by Parsons ES (1995), the biodegradation rate constant calculated for the POL site is at the low end of the range of values reported for total BTEX in the literature; these rates typically range from  $0.001$  to  $0.03 \text{ day}^{-1}$  (Chapelle, 1994; Buscheck *et al.*, 1993; Wiedemeier *et al.*, 1995). Therefore, this degradation rate is likely conservative. A biodegradation rate constant of  $0.0021 \text{ day}^{-1}$  is approximately equivalent to a contaminant half-life of 330 days.

This biodegradation rate expresses the quantity of contaminant mass being removed from the saturated media that cannot be explained by nondestructive attenuation processes such as dispersion and adsorption. The effects of both aerobic and anaerobic destructive attenuation processes are included in the site-specific biodegradation rate constant estimates. The potential for additional mass to leach from overlying soils into groundwater, adding additional mass to the groundwater which is being biodegraded, was not factored into the rate estimates. As a result, the estimated rates likely underestimate the effectiveness of biodegradation processes at the site.

The POL site data also can be used to calculate compound-specific biodegradation rates. A benzene biodegradation rate of approximately  $0.0004 \text{ day}^{-1}$  was calculated for the POL site using the method of Buscheck and Alcantar (1995) described in Appendix F. This rate is approximately equivalent to a contaminant half life of 1,732 days. Benzene decay rates reported in the literature are typically at least one order of magnitude higher, ranging from  $0.003$  to  $0.095 \text{ day}^{-1}$  (Wiedemeier *et al.*, 1995; MacIntyre *et al.*, 1993; Kemblowski *et al.*, 1987; Chiang *et al.*, 1989; Wilson *et al.*, 1990; Howard *et al.*, 1991; Chapelle *et al.*, 1996). Biodegradation rates for most of the other COPCs at the MOGAS site should be the same order of magnitude as the rate calculated for benzene. TMB compounds are reported to be relatively resistant to biodegradation under anaerobic conditions, and therefore may not degrade significantly until more aerobic conditions are present in or near the drainage ditch.

#### **6.4 EVIDENCE OF CONTAMINANT BIODEGRADATION VIA MICROBIALLY CATALYZED REDOX REACTIONS**

As described in Section 6.3.2, historical site data do not conclusively demonstrate that the COPCs are biodegrading in saturated soils and groundwater at the MOGAS site. Part of the uncertainty surrounding the historical concentration trend analysis relates to the uncertainty regarding the actual dissolved BTEX concentration in downgradient well MW-112 during the 1988 sampling event (ERM, 1990). The

presence of both increasing and decreasing temporal concentration trends, and the general absence of reliable historical data for all of the COPCs also contribute to the inconclusiveness of the trend analysis. However, application of spatial regression techniques to calculate site-specific biodegradation rates for BTEX and benzene at the adjacent POL bulk fuel storage area (Parsons ES, 1995) indicates that biodegradation is occurring, although potentially at slower rates than those reported in the technical literature.

There is a third line of evidence that can be used to investigate whether COPCs are biodegrading in saturated soil and groundwater at the MOGAS site. The COPCs can be utilized as electron donors in biologically mediated reduction/oxidation (redox) reactions under a wide range of geochemical conditions. Because the COPCs can be utilized in biologically mediated redox reactions, analytical data on potential electron acceptors can be used as geochemical indicators of COPC biodegradation (Salanitro, 1993; McCallister and Chiang, 1994; Wiedemeier *et al.*, 1995; Borden *et al.*, 1995). Reductions in the concentrations of oxidized chemical species that are used by microorganisms to facilitate the oxidation of fuel hydrocarbons within contaminated media can indicate that contaminants are biodegrading. Alternately, an increase in the metabolic byproducts resulting from the reduction of electron acceptors can be used as an indicator of contaminant biodegradation. The availability of potential electron acceptors for participation in contaminant biodegradation reactions can be used to estimate the total contaminant mass that can be biodegraded over time at these sites. This information can be used to infer the occurrence of biodegradation.

#### 6.4.1 Relevance of Redox Couples in Biodegradation

Microorganisms obtain energy to replenish enzymatic systems and to reproduce by oxidizing organic matter. Biodegradation of the COPCs is the result of a series of redox reactions that maintain the charge balance within the natural environment. Microorganisms facilitate the degradation of fuel-related compounds by transferring electrons from the electron donor (i.e., BTEX, TMB, naphthalene, and native organic carbon) to available electron acceptors. Electron acceptors are elements or compounds that occur in relatively oxidized states and can participate in redox reactions involving BTEX or other fuel-related compounds. Native electron acceptors known to be present in saturated soil and groundwater at the MOGAS site include oxygen, sulfate, ferric iron, and carbon dioxide. Nitrate was detected only sporadically, and does not appear to be a significant electron acceptor at this site.

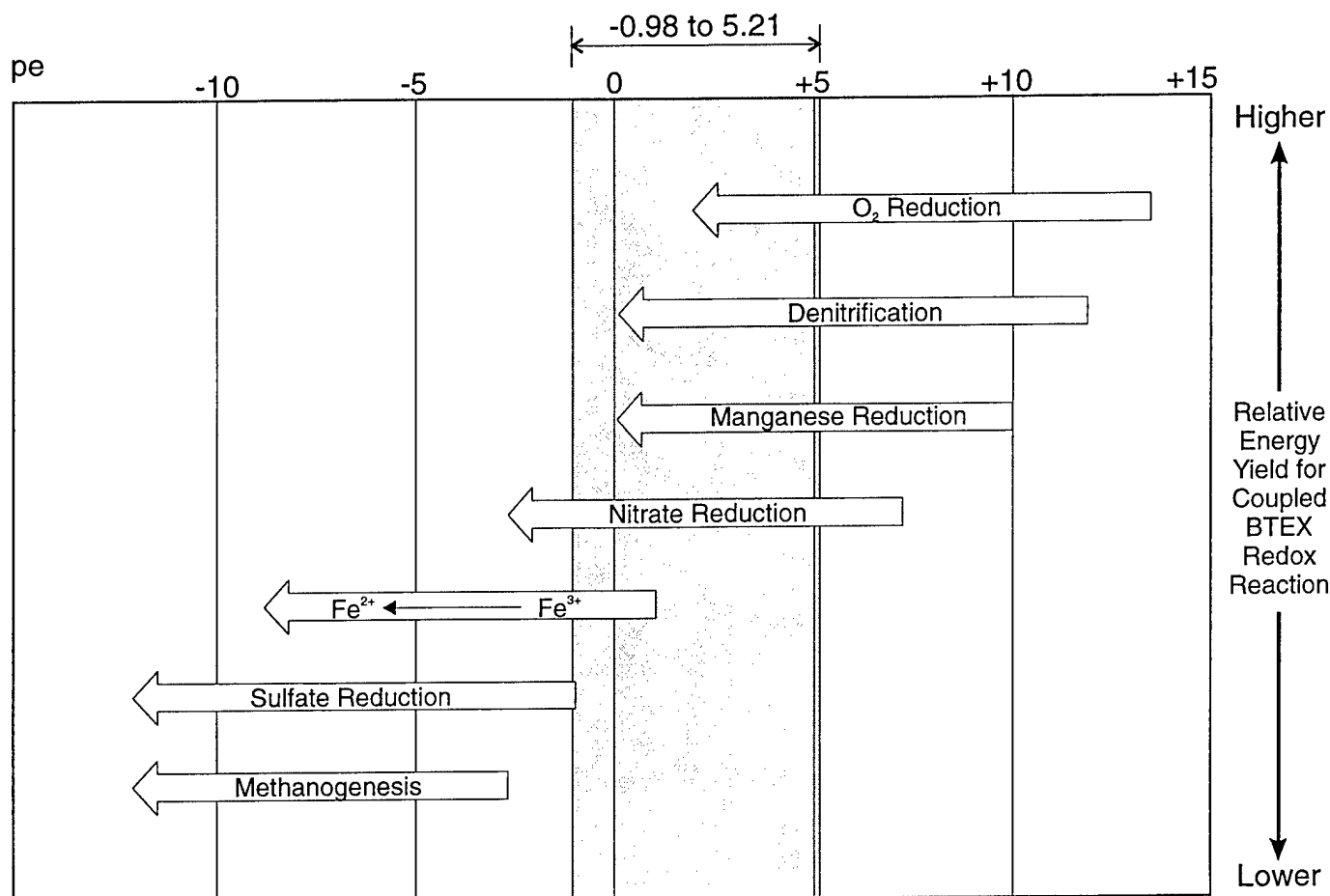
Microorganisms facilitate biodegradation of hydrocarbon compounds to produce energy for their use. The amount of energy that can be released when a reaction occurs or that is required to drive the reaction to completion is quantified by the free energy of the reaction (Stumm and Morgan, 1981; Bouwer, 1994; Chapelle, 1993; Godsey, 1994; Mueller *et al.*, 1994). Microorganisms are able to utilize electron transport systems and chemiosmosis to combine energetically favorable and unfavorable reactions to produce energy for life processes; however, they will facilitate only those reactions that will yield energy. By coupling the oxidation of the COPCs, which requires energy, to the reduction of other compounds (e.g., oxygen, ferric iron, sulfate, and carbon dioxide), which yields energy, the overall reaction will yield energy. Detailed

information on the redox reactions required to biodegrade each of the BTEX compounds is included in Appendix F. The reader is encouraged to review this information to more fully understand the chemical basis of biodegradation.

Figure 6.3 illustrates the sequence of microbially mediated redox processes based on the amount of free energy released for microbial use. In general, reactions yielding more energy tend to take precedence over processes that yield less energy (Stumm and Morgan, 1981; Godsey, 1994; Reinhard, 1994). As Figure 6.3 shows, oxygen reduction would be expected to occur in an aerobic environment with microorganisms capable of aerobic respiration because oxygen reduction yields significant energy (Bouwer, 1992; Chapelle, 1993). However, once the available oxygen is depleted and anaerobic conditions dominate the interior regions of the contaminant plume, anaerobic microorganisms can utilize the other electron acceptors present at the MOGAS site in the following order of preference: ferric iron, sulfate, and finally carbon dioxide. Each successive redox reaction provides less energy to the system, and each step down in redox energy yield would have to be paralleled by an ecological succession of microorganisms capable of facilitating the pertinent redox reactions.

The expected sequence of redox processes also is a function of the oxidizing potential (Eh) of the groundwater. The oxidizing potential measures the relative tendency of a solution or chemical reaction to accept or transfer electrons. The oxidizing potential of the groundwater can be measured in the field. This measurement can be used as a crude indicator of which redox reactions may be operating at a site. This field measurement can then be expressed as pe, which is the hypothetical measure of the electron activity associated with a specific Eh. A high pe means that the solution or redox couple has a relatively high oxidizing potential.

Microorganisms can only facilitate the biodegradation (oxidation) of the COPCs using redox couples that have a higher oxidizing potential than the contaminants. Appendix F includes tables that show that redox couples including nitrate, oxygen, ferric iron, sulfate, and carbon dioxide all have higher oxidizing potentials than the redox couples including the fuel hydrocarbon COPCs. This is why these electron acceptors can be used to oxidize the fuel hydrocarbon compounds. However, as described above, the TMB compounds are relatively resistant to anaerobic biodegradation. Therefore, once the dissolved oxygen supply in the groundwater is depleted, the remaining TMBs may be relatively persistent. The reduction of highly oxidized species results in an overall decrease in the oxidizing potential of the groundwater. As shown in Figure 6.3, the reduction of oxygen and nitrate will reduce the oxidizing potential to levels at which ferric iron ( $\text{Fe}^{3+}$ ) reduction can occur. As each chemical species that can be used to oxidize the contaminants is exhausted, the microorganisms are forced to use other available electron acceptors with lower oxidizing capacity. When sufficiently low (negative) pe levels have been developed as a result of these redox reactions, sulfate reduction and methanogenesis can occur almost simultaneously (Stumm and Morgan, 1981).



## Notes

 Range of pe measured at the MOGAS site.

1. These reactions would be expected to occur in sequence if the system is moving toward equilibrium.
2. These redox processes occur in order of their energy-yielding potential (provided microorganisms are available to mediate a specific reaction). Reduction of a highly oxidized species decreases the pe of the system.
3. The pe of the system determines which electron acceptors are available for COPC oxidation.
4. Redox sequence is paralleled by an ecological succession of biological mediators.

**FIGURE 6.3**

### SEQUENCE OF MICROBIALY MEDIATED REDOX PROCESSES

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**

Denver, Colorado

The distribution of the oxidizing potentials (expressed as measured Eh values or ORPs) in shallow groundwater at the MOGAS site is shown on Figure 6.4. Values of pe can be calculated from measured Eh values (in millivolts) using the following equation:

$$pe = \frac{Eh + 241}{59.16}$$

The deviation of this equation is contained in Appendix C. The range of pe in the groundwater at the MOGAS site, based on Eh measurements collected in the field, is -0.98 to 5.21. These data imply that oxygen, nitrate, and ferrous iron may be used to biodegrade contaminants at the MOGAS site (Figure 6.3). However, as mentioned above, the general absence of detectable nitrate concentrations in groundwater indicates that this compound is not a significant electron acceptor at this site. Analytical data on oxidized and reduced species are presented in the next sections to verify which electron acceptors are being used to biodegrade the COPCs in saturated soil and groundwater at the MOGAS site.

#### 6.4.2 Dissolved Oxygen Concentrations

Almost all types of fuel hydrocarbons can be biodegraded under aerobic conditions (Borden, 1994). Mineralization of fuel hydrocarbons to carbon dioxide and water under aerobic conditions involves the use of oxygen as a cosubstrate during the initial stages of metabolism, and as a terminal electron acceptor during the later stages of metabolism for energy production (Higgins and Gilbert, 1978; Gibson and Subramanian, 1984; Young, 1984). The reduction of molecular oxygen during the oxidation of the COPC compounds yields a significant amount of free energy to the system that microorganisms can utilize (Appendix F).

DO concentrations were measured at selected groundwater monitoring wells and monitoring points in January and August-September 1995. Figure 6.5 presents August-September 1995 analytical results for DO by sampling location. At sampling locations where a DO analysis was not performed in August-September, the January 1995 value is used when available. The generally low DO concentrations both inside and outside of the contaminant plume indicate that the groundwater system is naturally low in DO, that DO is not an important electron acceptor at this site, and that the degradation mechanisms operating at the site are primarily anaerobic.

Except at sampling locations MOC-04 and MW-05, DO concentrations from shallow groundwater monitoring locations were less than 1 mg/L. As expected, the lowest concentrations in the shallow groundwater zone were detected at and near well MW-112, where the most elevated dissolved BTEX concentrations were detected. Background (upgradient to crossgradient) DO concentrations in the shallow groundwater zone, which were estimated using data from two wells located outside or on the margin of the BTEX plume (MW-07 and MW-111) averaged 0.42 mg/L. The potential for higher DO concentrations is indicated by the values measured at MOC-04 (1.30 mg/L) and MW-05 (1.10 mg/L). However, these higher concentrations do not appear to be widespread in upgradient portions of the site. DO concentrations measured south of the drainage ditch are, on the average, slightly higher than near the

ditch on the north side, reflecting the relative lack of dissolved BTEX in groundwater south of the ditch. DO concentrations in the deep groundwater zone, measured at wells MW-12, MW-15, MW-16, and MW-18, also were low, ranging from 0.01 to 0.20 mg/L.

The relative insignificance of aerobic degradation at this site, inferred from the low DO concentrations measured across the entire site is consistent with the low to moderate magnitude of the measured Eh levels (ORPs) at the site (Figure 6.4).

#### 6.4.3 Dissolved Nitrate and Nitrite Concentrations

Once anaerobic conditions prevail in the groundwater, nitrate can be used as an electron acceptor by indigenous facultative anaerobic microorganisms to mineralize hydrocarbons via either denitrification or nitrate reduction processes. Nitrate can function as an electron acceptor in microbially facilitated fuel hydrocarbon degradation reactions only if the groundwater system has been depleted of oxygen (i.e., the groundwater must be functionally anaerobic). Oxygen is toxic to the enzyme systems used for electron transfer and energy production of nitrate-reducing microorganisms (McCarty, 1972). Denitrification is the most energetically favorable of the redox reactions likely to be involved in the oxidation of BTEX and TMB compounds (Appendix F). Although the oxidation of the BTEX and TMB compounds and naphthalene by nitrate reduction also will yield significant amounts of free energy for microbial use, nitrate reduction is not as energetically favorable as other potential redox reactions. However, nitrate reduction may take precedence over denitrification as the groundwater becomes more reducing.

Phase I groundwater samples collected in January 1995 were analyzed for the total nitrogen (nitrate plus nitrite). Individual concentrations for both nitrate and nitrite were obtained for the Phase II samples collected in August and September 1995. In January 1995, nitrate/nitrite was detected at only 4 of 16 sampled locations. Two of the four locations (MOC-08 and MOC-11) are located upgradient from the former UST locations, and the remaining two locations (MOC-05 and MOC-07) are located downgradient. Detected nitrate/nitrite concentrations ranged from 0.07 to 0.08 mg/L, which is slightly above the detection limit of 0.05 mg/L.

Nitrate was detected in only two of 32 samples obtained from the shallow groundwater zone during the Phase II (August-September 1995) sampling event. The two detections occurred south of the southern ditch at wells MW-04 (0.069 mg/L) and MW-14 (0.082 mg/L). Low concentrations of nitrate also were detected in two deeper wells, MW-08 and MW-16, at concentrations of 0.06 and 0.066 mg/L, respectively. Similarly, nitrite also was detected in only two of the 32 shallow groundwater zone samples. Both detections occurred downgradient from the former UST locations at monitoring points MOC-05 (0.1 mg/L) and MOC-10 (0.12 mg/L), suggesting that some limited nitrate reduction is occurring in shallow groundwater beneath the site. Nitrite was not detected in samples from the deeper wells at the site.

The general absence of detectable nitrate and nitrite concentrations in groundwater both upgradient and downgradient from the former UST locations indicates that

denitrification and nitrate reduction are generally not important processes promoting the biodegradation of petroleum-related compounds in the groundwater.

#### 6.4.4 Ferrous Iron Concentrations

Although relatively little is known about the anaerobic metabolic pathways involving the reduction of ferric iron ( $\text{Fe}^{3+}$ ), this process has been shown to be a major metabolic pathway for some microorganisms (Lovley and Phillips, 1988; Chapelle, 1993). The reduction of ferric iron results in the formation of ferrous iron ( $\text{Fe}^{2+}$ ). Elevated concentrations of ferrous iron are often found in anaerobic groundwater systems. These concentrations once were attributed to the spontaneous and reversible reduction of ferric oxyhydroxides, which are thermodynamically unstable in the presence of organic compounds such as BTEX, TMB, and naphthalene. However, recent evidence suggests that the reduction of ferric iron cannot proceed at all without microbial mediation (Lovley and Phillips, 1988; Lovley *et al.*, 1991; Chapelle, 1993). None of the common organic compounds found in low-temperature, neutral, reducing groundwater could reduce ferric oxyhydroxides to ferrous iron under sterile laboratory conditions (Lovley *et al.*, 1991). This means that the reduction of ferric iron requires mediation by microorganisms with the appropriate enzymatic capabilities.

To determine if ferric iron is being used as an electron acceptor for COPC biodegradation at the MOGAS site, ferrous iron concentrations were measured at selected groundwater monitoring wells and monitoring points in January and August-September 1995. Figure 6.6 presents the analytical results for ferrous iron in groundwater for the August-September samples. If a monitoring well/point was not sampled during the Phase II event, then the Phase I (January) concentration is reported. The three highest ferrous iron concentrations (ranging from 6.8 mg/L to 17.7 mg/L) were detected near and downgradient from the former UST locations, in areas characterized by substantially elevated dissolved BTEX concentrations. Ferrous iron concentrations in crossgradient areas east and west of the UST locations were generally relatively low (less than 1 mg/L). The correlation between elevated dissolved hydrocarbon concentrations and elevated ferrous iron concentrations is a strong indicator that iron-reducing microorganisms are using ferric iron to oxidize the contaminants because the reduction of ferric iron cannot proceed without microbial intervention.

Measured ORPs in the area between the former UST locations and the ditch range from -207 to -288 millivolts (mV), and average approximately -240 mV (Figure 6.4). The average pe value is therefore approximately 0, which is within the feasible range for the occurrence of ferric iron reduction, as shown on Figure 6.3.

#### 6.4.5 Sulfate Concentrations

Sulfate also may be used as an electron acceptor during microbial degradation of fuel hydrocarbons under anaerobic conditions (Grbic-Galic, 1990). This redox reaction is commonly called sulfate reduction. Sulfate is reduced to sulfide during the oxidation of petroleum compounds. The presence of decreased concentrations of sulfate (and possibly increased concentrations of sulfide) in the source area relative to background

concentrations indicates that sulfate may be participating in redox reactions at a site. To investigate the potential for sulfate reduction at the MOGAS site, total sulfate and sulfide concentrations were measured at groundwater monitoring wells and monitoring points during the January and August-September 1995 sampling events.

Figures 6.5 and 6.6 show the August-September 1995 analytical results for sulfate and sulfide in groundwater. If a monitoring well/point was not sampled during the Phase II event, then the Phase I (January 1995) concentration is reported. The lowest sulfate concentrations were detected downgradient from the former UST locations, in the same areas where elevated levels of dissolved petroleum concentrations were detected. In these areas, sulfate concentrations are below 10 mg/L. This correlation is another indication that anaerobic biodegradation of dissolved petroleum constituents is occurring through the microbially mediated process of sulfate reduction. Substantially higher sulfate concentrations, in excess of 40 mg/L, were detected in more upgradient areas (wells MW-111, MW-07, and monitoring point MOC-08) and south of the drainage ditch (wells MW-04 and MW-14). The presence of elevated sulfate concentrations south of the ditch is consistent with the observation that the ditch effectively captures most of the shallow groundwater migrating from the former UST locations. The detection of sulfate at a concentration of 122 mg/L at well MW-02 is an indication that the area between the UST locations is substantially less contaminated than the areas directly south of the UST locations.

Except for low concentrations at MW-3 and MW-111, sulfide was not detected in wells outside the area of detectable levels of dissolved fuel hydrocarbon contamination. The depletion of sulfate and production of sulfide within the contaminated area indicates that sulfate is acting as an electron acceptor at this site.

The distribution of low ORPs (and pe values) correlates with the distribution of reduced sulfate concentrations at the MOGAS site; however, measured groundwater ORPs at the sites (Figure 6.3) are higher than would be expected for the sulfate-reducing conditions implied by the observed sulfate distribution (Figure 6.5). Sulfate reduction can only be mediated in reducing conditions (low ORP and pe). Measured ORPs at the MOGAS site are generally too high (not sufficiently negative) to suggest that sulfate reduction could be prominent at the site. It is likely that the platinum electrode probes are not sensitive to the sulfate/sulfide redox couple. This is a common problem associated with measuring ORP using field instruments. Many authors have noted that measured ORP data alone cannot be used to reliably predict the electron acceptors that may be operating at a site (e.g., Stumm and Morgan, 1981; Godsey, 1994; Lovley *et al.*, 1994). Nevertheless, integrating ORP measurements with analytical data on reduced and oxidized chemical species allows a more thorough and reasonable interpretation of which electron acceptors are being used to biodegrade site contaminants.

#### **6.4.6 Methane and Carbon Dioxide Concentrations**

On the basis of free energy yield and the oxidizing potential of the site groundwater, the carbon dioxide-methane ( $\text{CO}_2\text{-CH}_4$ ) redox couple also could be used to oxidize fuel hydrocarbon compounds to carbon dioxide and water once the groundwater is

sufficiently reducing. To attain these reducing levels, other highly oxidizing chemical species such as oxygen, nitrate, and sulfate must be reduced. This redox reaction is called methanogenesis or methane fermentation. Methanogenesis yields the least free energy to the system in comparison to other chemical species (Figure 6.3 and Appendix F). The presence of methane in groundwater at elevated concentrations relative to background concentrations is a good indicator of methane fermentation.

Dissolved methane concentrations were measured at selected groundwater monitoring wells and monitoring points in January and August-September 1995. Figure 6.6 presents the August-September analytical data for methane by sampling location. If a monitoring well/point was not sampled during the Phase II event, then the Phase I (January) concentration is reported. The highest methane concentrations were detected near and downgradient from the former UST locations, with the most elevated methane concentration (3.17 mg/L, measured in January 1995) occurring at temporary monitoring point MOV-01-03. The January 1995 groundwater sample from this point had a dissolved BTEX concentration of 37,090 µg/L. In other portions of the study area, methane concentrations were below 0.5 mg/L, and ranged as low as 0.037 mg/L. The presence of methane in contaminated groundwater at the MOGAS site indicates that some biodegradation is occurring in the core of the dissolved contaminant plume via methanogenesis. Measured ORPs at the MOGAS site are too high (not sufficiently negative) on the average to suggest that methane production via methanogenesis is occurring. However, as discussed in Section 6.4.5, this is a common problem associated with measuring ORP using field instruments.

## 6.5 THEORETICAL ASSIMILATIVE CAPACITY ESTIMATES

The preceding discussions have been devoted to determining if the COPC compounds are biodegrading at the MOGAS site. Analytical data on reduced and oxidized chemical species indicate that indigenous microorganisms are facilitating the oxidation of fuel hydrocarbons and the reduction of electron acceptors to generate free energy for cell maintenance and production. The question of how much contaminant mass can be biodegraded must be addressed to assess the full potential for long-term intrinsic remediation at the sites to attain the site-specific Tier 2 cleanup goals throughout the contaminant plumes (Section 7).

Mass-balance relationships can be used to determine how much contaminant mass can be degraded by each of the redox reactions that microorganisms might use to make free energy available for cell maintenance and production. The stoichiometric relationship between the contaminant and the electron acceptor can be used to estimate the expressed assimilative capacity of the groundwater. Once the redox reactions operating at these sites were defined, it is possible to estimate theoretically how much contaminant mass can be assimilated or oxidized by available electron acceptors. This analysis, when coupled with the biodegradation rate information discussed earlier (Section 6.3.4), provides the basis for determining the potential for continued COPC mass reduction in saturated media at the site.

Appendix F presents the coupled redox reactions that represent the biodegradation of each of the COPCs. The tables in Appendix F also present the stoichiometric mass

ratios of electron acceptors needed to oxidize the COPCs in saturated soils and groundwater. These stoichiometric mass ratios can be used to estimate the assimilative capacity of saturated media at the MOGAS site. This is accomplished by first determining the initial mass of each electron acceptor available in the groundwater. Data on these chemical species were collected at sampling locations upgradient from the former UST locations (i.e., sampling location MW-111). As groundwater slowly migrates downgradient into the source area, electron acceptors are brought into contact with hydrocarbon-degrading microorganisms and site contamination. The change in the electron acceptor mass from upgradient sampling locations to sampling locations within the source area is divided by the mass of electron acceptors required to mineralize each of the fuel hydrocarbon COPCs to estimate the expressed intrinsic capacity of the groundwater to biodegrade these compounds.

Estimates of the background concentrations of all of the electron acceptors that appear to be operating at the site to biodegrade the COPCs are listed in Table 6.1. These concentrations are used to calculate the available or expressed assimilative capacity of each electron acceptor for total BTEX and for the combined COPCs (BTEX plus naphthalene and the TMB isomers) based on the mass stoichiometric relationships presented in detail in Appendix F. Table 6.1 also presents the source area concentrations of the biodegradation byproducts ferrous iron and methane. These concentrations are used to back-calculate the expressed assimilative capacity that is attributable to ferric iron and methanogenesis. On the basis of these calculations, the saturated soils and groundwater at the MOGAS site has the intrinsic capacity to eventually oxidize a concentration of approximately 13,760  $\mu\text{g/L}$  of total BTEX or a total COPC concentration of 13,290  $\mu\text{g/L}$ .

The BTEX assimilative capacity calculated for the adjacent POL site (Parsons ES, 1995) was 28,300  $\mu\text{g/L}$ , with sulfate reduction and methanogenesis acting as the dominant biodegradation processes. This capacity is substantially higher than that calculated for the MOGAS site because the maximum methane concentration detected at the POL site was nearly 18 mg/L, as opposed to approximately 3 mg/L at the MOGAS site. Nevertheless, this estimate of expressed assimilative capacity is a strong indicator that biodegradation is occurring; however, because the biodegradation reactions are rate-limited, some dissolved contaminants are migrating to and discharging into the southern drainage ditch, potentially impacting receptors exposed to surface water in the ditch. The concept of assimilative capacity is discussed further in the following paragraphs.

The estimated assimilative capacity for the MOGAS site essentially represents an upper-bound estimate of the intrinsic mass reduction capability of the groundwater and saturated soils at the MOGAS site. The estimate identifies how much contaminant mass can be theoretically oxidized as one pore volume travels through the plume core. So, although the capacity is expressed in  $\mu\text{g/L}$ , the capacity is actually an estimate of the micrograms of contaminant mass that can be degraded in the volume of groundwater traveling through the core plume. A closed system containing 2 liters of water can be used to help visualize the physical meaning of assimilative capacity. Assume that the first liter contains no fuel hydrocarbons, but it contains fuel-degrading microorganisms and has an assimilative capacity of exactly "x" mg of fuel

**TABLE 6.1**  
**ESTIMATE OF EXPRESSED ASSIMILATIVE CAPACITY OF**  
**SATURATED SOIL AND GROUNDWATER**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Biodegradation Process	Indicator Parameter	Background Concentration <sup>a/</sup> of Indicator Parameter (µg/L)	Utilized Electron Acceptor Mass (µg/L)	BTEX Assimilative Capacity <sup>b/</sup> (µg/L)	Combined COPC Assimilative Capacity <sup>b/</sup> (µg/L)
Oxygen Reduction	Dissolved Oxygen	420	370	118	118
Iron Reduction <sup>c/</sup>	Ferrous Iron	3,340	14,360	659	472
Sulfate Reduction	Sulfate	43,830	42,970	9,024	9,143
Methanogenesis	Methane	78	3,092	3,964	3,554
			<b>Total</b>	<b>13,765</b>	<b>13,287</b>
			<b>1995 Maximum</b>	<b>47,300</b>	<b>50,900</b>

<sup>a/</sup> Background concentrations determined using data from wells MW-07 and MW-111.

<sup>b/</sup> Calculated based on the ratio of the total mass of electron acceptor required to oxidize a given mass of total benzene, toluene, and ethylbenzene (BTE) or total COPC mass, assuming no other source of oxidizing demand (Appendix F).

<sup>c/</sup> This represents the reduced form of the electron acceptor. Assimilative capacity is expressed only as an estimate.

hydrocarbons. The second liter has no assimilative capacity; however, it contains fuel hydrocarbons. As long as these 2 liters of water are kept separate, the biodegradation of fuel hydrocarbons will not occur. If these 2 liters are combined in a closed system, biodegradation will commence and continue until the fuel hydrocarbons are depleted, the electron acceptors are depleted, or the environment becomes acutely toxic to the fuel-degrading microorganisms. Assuming a nonlethal environment, if less than "x" mg of fuel hydrocarbons are in the second liter, all of the fuel hydrocarbons will eventually degrade given a sufficient time; likewise, if greater than "x" mg of fuel hydrocarbons were in the second liter of water, only "x" mg of fuel hydrocarbons would ultimately degrade.

This example shows, that in a closed system, the measured expressed assimilative capacity should be equivalent to the loss in contaminant mass; however, the groundwater beneath a site is an open system. Electron acceptors continually enter the system from upgradient flow and the infiltration of precipitation. Furthermore, contaminant mass can be added to the system through dissolution or leaching from residual LNAPL. This means that the assimilative capacity is not fixed as it would be in a closed system, and therefore cannot be compared directly to contaminant concentrations in the groundwater. Rather, the expressed assimilative capacity of groundwater is intended to serve as a qualitative tool. The fate of BTEX in groundwater and the potential impact to receptors is dependent on the relationship between the kinetics of biodegradation and the solute transport velocities (Chapelle, 1994).

It is significant that assimilative capacity is not fixed because BTEX concentrations considerably higher than the expressed capacity can be attenuated over time as a result of the continual flushing through the system of uncontaminated water containing undepleted electron acceptor concentrations. The fact that assimilative capacity is not fixed also is significant because it means that concentrations of TMB or other water-soluble hydrocarbon compounds can decrease over time as a result of mass removal mechanisms without interfering with continued BTEX biodegradation.

## **6.6 PREDICTING CONTAMINANT TRANSPORT AND FATE**

Understanding the effects of natural physical, chemical, and biological processes on chemicals in the subsurface is an important step in determining potential long-term risks associated with chemical migration in the environment. The behavior of COPCs under the influence of these processes must be quantified to predict the extent that soil COPCs could leach from residual LNAPL and dissolve into groundwater; to assess the expected persistence, mass, concentration, and toxicity of dissolved COPCs over time at the site; and to estimate potential receptor exposure-point concentrations. If destructive and nondestructive attenuation processes can minimize or eliminate the concentration of contaminants to which a receptor could be exposed, remedial action may not be warranted because no reasonable exposure pathway exists or the exposure pathway would result in insignificant risks. The focus of this final section is to predict how the COPCs will be transported and transformed over time in soil and groundwater based on site data and a site-specific contaminant transport and fate models.

### 6.6.1 Volatilization from Subsurface Sources

Maximum detected soil gas concentrations were conservatively compared to air RBSLs to define ambient atmosphere COPCs in Section 4.3.2. However, as discussed previously, this comparison is overly conservative because soil gas measurements do not reflect the exposure-point concentrations in outdoor ambient air or within onsite structures. To determine whether subsurface sources (i.e., contaminated soils and dissolved contamination) could cause exposure-point concentrations in either outdoor or indoor air that may pose an unacceptable risk to potential onsite receptors via the inhalation exposure route, several different kinds of chemical flux and atmospheric transport equations were coupled to simulate the concentrations of volatile COPCs present in outdoor ambient air under normal atmospheric conditions and the concentrations of volatile COPCs accumulating within onsite buildings. Most of the equations are based on the predictive contaminant migration equations presented by ASTM (1995) in the *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites*. However, the equations for estimating flux into and resultant concentration within an enclosed space as presented in the ASTM (1995) guide are incorrect. Consequently, two simple, alternate models [i.e., the Farmer Model (USEPA, 1992b) and the indoor air dispersion model (Michelson *et al.*, 1993)] were used instead.

Three different types of COPC migration equations were used to predict the transport of VOCs from subsurface sources through unsaturated soils and manmade structures (e.g., building foundations), and within ambient air. Equilibrium partitioning equations were used to estimate the mass of volatile COPCs that theoretically could partition from dissolved contamination and contaminated soil. The theoretical source term based on equilibrium partitioning equations is expected to overestimate the COPC mass present in the vapor phase at the MOGAS site. These equations assume linear partitioning and a constant and nondiminishing source (e.g., no reduction in source term as a result of volatilization, biodegradation, or other attenuation mechanisms). In addition to these conservative assumptions, the COPC mass contributed from dissolved contamination and contaminated soil was cumulatively accounted for in the resultant theoretical source term. For comparison, the maximum measured soil gas concentrations also were used to represent the observed subsurface source term. Thus, a range of possible air quality impacts were quantified by using both a theoretical (upper bound) and observed source term.

Flux equations were then used to estimate that mass of volatile COPCs that migrated to the target mixing area (i.e., outdoor ambient atmosphere and indoor building space). Simple "box" mixing equations were used to translate flux measurements into predicted exposure-point concentrations for air within the outdoor and indoor breathing zones. Outdoor air quality impacts were conservatively estimated assuming that volatile COPCs diffuse/convect through native soils only (i.e., the asphalt pavement capping a portion of the site is not present), and that only minimal atmospheric dispersion above the flux area is possible (i.e., virtual upwind point-source dispersion assumption). Indoor air quality impacts were conservatively estimated by allowing COPCs to seep through foundation cracks and mix within a ventilated but confined structure. Both site-specific and conservative default values were used as input parameters. Neither of

these conservative conditions have actually been observed at this site. The predictive model equations and input parameters are presented in Table 6.2.

The maximum concentrations of BTEX compounds detected in site soils during the 1994 and 1995 sampling events (Law, 1994 and this investigation) were used in the equilibrium partitioning models. Since these sampling events occurred, a 3-month-long SVE pilot test was performed which significantly reduced VOC concentrations in the vadose zone. Therefore, the vapor migration model predictions discussed below are overly conservative and not representative of current site conditions.

The predictive migration model based on the equilibrium partitioning equations (as opposed to actual measured soil vapor concentrations) indicates that none of the BTEX compounds could migrate into air at potential outdoor exposure points at concentrations that exceed OSHA TWA PELs established in 1989. (Note: The 1989 PELs were invalidated in 1992, and less conservative PELs, originally established in 1971, are currently being enforced. However, the more conservative 1989 PELs are used here for comparison purposes). Except for benzene, all of the predicted outdoor exposure concentrations are at least one order of magnitude lower than the OSHA compound-specific, TWA PELs. The outdoor exposure concentration predicted for benzene is 22 percent less than the PEL. However, the predicted outdoor benzene exposure concentration ( $2.52 \text{ mg/m}^3$ ) does exceed the SCDHEC (1995) inhalation RBSL of  $2.2 \times 10^{-4} \text{ mg/m}^3$  (Table 4.9) by four orders of magnitude. Similarly, the predicted outdoor exposure concentrations for toluene, ethylbenzene, and xylenes exceed their respective SCDHEC (1995) inhalation RBSLs by one to three orders of magnitude.

It is important to note that the equilibrium partitioning equations, which are based on site-specific soil and groundwater sampling data, may tend to overestimate the mass of COPCs present in the vapor phase at the MOGAS site. As shown on Table 6.2, the theoretical equilibrium vapor-phase concentrations for each of the air COPCs computed using the partitioning equations ("predicted  $C_{v,eq}$ " in Table 6.2) were one to two orders of magnitude higher than the maximum concentrations measured in soil gas near the source area at the site ("measured  $C_{v,eq}$ ")

The maximum BTEX concentrations detected in soil vapor samples in September 1995 (Figure 5.1) were used in the less conservative (but more realistic) diffusion model that is based on measured soil gas concentrations. As described above, BTEX concentrations present in the soil vapor have since been significantly reduced by the SVE pilot test that began in October 1995. This model predicted an outdoor benzene exposure concentration of  $0.135 \text{ mg/m}^3$ , which is one order of magnitude less than the PEL for this compound. The outdoor exposure concentrations predicted for toluene, ethylbenzene, and xylenes were three to four orders of magnitude lower than their respective PELs. However, predicted concentrations of benzene and toluene exceeded their respective SCDHEC (1995) inhalation RBSLs by three orders of magnitude and 200 percent, respectively. Predicted concentrations of ethylbenzene and xylenes did not exceed their respective SCDHEC inhalation RBSLs.

The predictive migration model equations for indoor air indicate that subsurface sources at the MOGAS site are not expected to cause indoor air concentrations of the

**TABLE 6.2**  
**MODELING VOLATILIZATION FROM SUBSURFACE MEDIA**  
 MOGAS SITE CORRECTIVE ACTION PLAN  
 RISK-BASED APPROACH TO REMEDIATION  
 MYRTLE BEACH AFB, SOUTH CAROLINA

Equations		Input Parameters													
Equilibrium Partitioning: Vapor Phase above Dissolved Contamination															
$C_{v,eq} = (H * C_{w,eq})$		$C_{v,eq}$	Equilibrium vapor concentration (g/cm <sup>3</sup> )												
		H	Henry's law constant (dimensionless)												
		$C_{w,eq}$	Equilibrium dissolved concentration (g/ml)												
Equilibrium Partitioning: Vapor Phase above LNAPL															
$C_{v,eq} = (x_i P_i M_w / RT)$		$x_i$	Mole fraction of contaminant i												
		$P_i$	Vapor pressure of contaminant i (atm)												
		$M_w$	Molecular weight (g/mol)												
		RT	Gas constant*temperature (cm <sup>3</sup> -atm/mol)												
Equilibrium Partitioning: Vapor Phase in Contaminated Soils															
$C_{v,eq} = (HC_{soil}P_s) / (\phi_w + k_d P_s + H\phi_a)$		$C_{soil}$	Concentration of contaminant in soil (g/g-soil)												
		$P_s$	Soil bulk density (g-soil/cm <sup>3</sup> -soil)												
		$\phi_w$	Volumetric content of pore water (dimensionless)												
		$k_d$	Sorption coefficient (cm <sup>3</sup> -H <sub>2</sub> O/g-soil)												
		$\phi_a$	Volumetric content of pore vapor (dimensionless)												
		$\phi_T$	Total volumetric content in soil (dimensionless)												
		$D_{air}$	Diffusion coefficient in air (cm <sup>2</sup> -day)												
		$D_w$	Diffusion coefficient in water (cm <sup>2</sup> /day)												
		$R_v$	Porous media retardation (dimensionless)												
		$u_{v,max}$	Convective transport of vapors (cm/day)												
		d	Distance below ground to source (cm)												
		L	Downwind length of source area (cm)												
		$u_w$	Wind speed (cm/day)												
		$\delta$	Breathing height (cm)												
		$A_{bldg}$	Surface area of building (cm <sup>2</sup> )												
		$F_{crack}$	Fraction of cracks in foundation (dimensionless)												
		$A_{ir,exch}$	Air exchanges per year												
		$V_{bldg}$	Volume of building (cm <sup>3</sup> )												
		MF	Mixing factor (dimensionless)												
Measured Vapor Phase in Soils															
$C_{v,eq}$ = Maximum measured soil gas concentration															
Effective Vapor Diffusion Coefficient															
$D^{eff} = (\phi_a^{3.33} / \phi_T^{2.2}) * D_{air} + (1/H) * (\phi_w^{3.33} / \phi_T^{2.2}) * D_w$															
Maximum Vapor Flux to Open Space															
$F_{max} = R_v u_{v,max} C_{v,eq} - (R_v u_{v,max} C_{v,eq}) / [1 - \exp(-R_v u_{v,max} d / D^{eff})]$															
Ambient Outdoor Concentration (g/cm <sup>3</sup> )															
$C_{outdoor} = F_{max} L / u_w \delta$															
Maximum Vapor Flux to Enclosed Space															
$E_{max} = (D^{eff} C_{v,eq} \phi_a^{3.33}) / (\phi_T^{2.2} d)$															
Ambient Indoor Concentration (g/cm <sup>3</sup> )															
$C_{indoor} = (E_{max} A_{bldg} F_{crack}) / (A_{ir,exch} V_{bldg} MF)$															
Compound	H	$x_i$	$P_i$	$M_w$	$C_{soil}$	$D_{air}$	$D_w$	$k_d$	$C_{w,eq}$	Predicted $C_{v,eq}$	$C_{outdoor}$ (mg/m <sup>3</sup> )	Measured $C_{v,eq}$	$C_{outdoor}$ (mg/m <sup>3</sup> )	$C_{indoor}$ (mg/m <sup>3</sup> )	
Benzene	0.232	0.030	0.125	78	8.70E-05	8.04E+03	0.95	0.190	6.0E-06	7.81E-05	2.52E+00	6.45E-04	4.20E-06	1.35E-01	1.72E-04
Toluene	0.265	0.285	0.037	92	6.50E-04	7.34E+03	0.81	0.674	2.6E-05	2.62E-04	3.00E+01	1.98E-03	7.60E-06	8.69E-01	2.85E-04
Ethylbenzene	0.265	0.133	0.009	106	1.80E-04	6.57E+03	0.73	0.477	2.7E-06	8.53E-05	6.91E+00	5.76E-04	8.80E-07	7.13E-02	2.95E-05
Xylenes	0.289	0.554	0.260	106	1.00E-03	6.22E+03	0.73	1.199	1.4E-05	8.47E-04	1.72E+02	5.42E-03	1.80E-06	3.66E-01	5.71E-05

BTEX compounds to exceed the air RBSLs presented in Table 4.9 or the 1989 OSHA PELs. The predictive migration model indicates that indoor air concentration of each of the BTEX compounds are conservatively expected to be at least an order of magnitude below the SCDHEC (1995) RBSLs for air, which are the most conservative comparison values and are well below detection limits for most analytical methods. Therefore, no engineered remediation is warranted to prevent migration of volatile COPCs into indoor air at concentrations above the RBSLs.

#### 6.6.2 Estimating Leaching of COPCs from Saturated Soils

All of the soil COPCs (i.e., benzene, toluene, ethylbenzene, chlorobenzene, 1,3,5-TMB, and naphthalene) were identified based on exceedances of Tier 1 RBSLs that are protective of groundwater quality. The RBSLs used in the Tier 1 evaluation are "back-calculated" using an equilibrium partitioning calculation to establish residual soil concentrations that prevent leachate generation from sandy soils from exceeding federal MCLs in groundwater (SCDHEC, 1995). The equilibrium partitioning calculation assumes that contaminants either volatilize into pore air volume or desorb from the soil matrix into pore water that enters the groundwater. Once released into underlying groundwater, the contaminant is assumed to be subject to both nondestructive (i.e., sorption, volatilization, dilution with the receiving aquifer) and destructive (i.e., biodegradation) attenuation processes. All of these attenuation processes are incorporated into the RBSLs using a default dilution/attenuation factor (DAF).

Groundwater is not currently extracted from the surficial aquifer underlying the MOGAS site to support drinking water demands, and extraction for this purpose in the future is not expected. Therefore, onsite workers are not likely to ingest contaminated groundwater (also see Section 7). However, defining how these fuel hydrocarbon compounds could partition from saturated soil and dissolve into groundwater over time can facilitate prediction of future groundwater quality impacts.

A site-specific equilibrium partitioning relationship was used to model how an indicator soil COPC (benzene) adsorbed to soil particles is expected to leach from saturated soils and dissolve into groundwater. Partitioning calculations were completed for benzene because this compound has the lowest Tier 1 RBSL (Table 4.7) and SSTL (Section 7). Therefore, the amount of time required to leach benzene from soils and achieve the RBSLs should be conservative with respect to the other soil COPCs. A chemical-specific distribution partition coefficient ( $K_d$ ) that is based on site-specific soil and groundwater analytical data was used to describe how much benzene mass remains associated with the soil matrix and how much mass will dissolve into adjacent pore water.

The  $K_d$  value is incorporated into a simple batch-flushing model presented by USEPA (1988) in which the total volume of contaminated soil is continuously or periodically flushed with groundwater. Contaminants sorbed to the soil matrix are predictively modeled to leach from the soil into the groundwater, and the resultant decrease in soil contaminant concentrations with time is simulated. As each new pore volume of groundwater comes in contact with the soil, a new equilibrium between the soil and groundwater is reached. In this way, both the soil and groundwater

concentrations are reduced with each successive pore-volume "flush". The leaching model calculations and input values are more fully described in Appendix F.

The batch flushing model was used to estimate the long-term effects of leaching on contaminant concentrations in soil (and groundwater) at the site. It is important to note that this calculation only accounts for the physical and chemical processes involved in COPC leaching from saturated soils. This calculation does not consider how much COPC mass could be lost from saturated soils due to the effects of biodegradation over time. Because site data indicate that the soil contamination is present both above and below the water table, precipitation infiltration through the vadose zone will also cause contaminant leaching. This leaching will be minimal beneath the paved portion of the site.

The site-specific leaching calculations are summarized in Table 6.3 and graphically shown in Figure 6.7. The predictive model results suggest that substantial soil benzene concentrations will persist for a long period of time without engineered remediation. The model predicts that the maximum concentration of benzene in saturated soils (29,000  $\mu\text{g/kg}$ ) will be reduced below 10,000, 1,000, and 100  $\mu\text{g/kg}$  after approximately 30 years, 100 years, and 170 years, respectively. These time frames are not precise, but are conservative estimates based on an assumed soil porosity, soil bulk density, and  $K_d$  for benzene (Appendix F).

### **6.6.3 Predicting Fate and Transport of Dissolved Benzene**

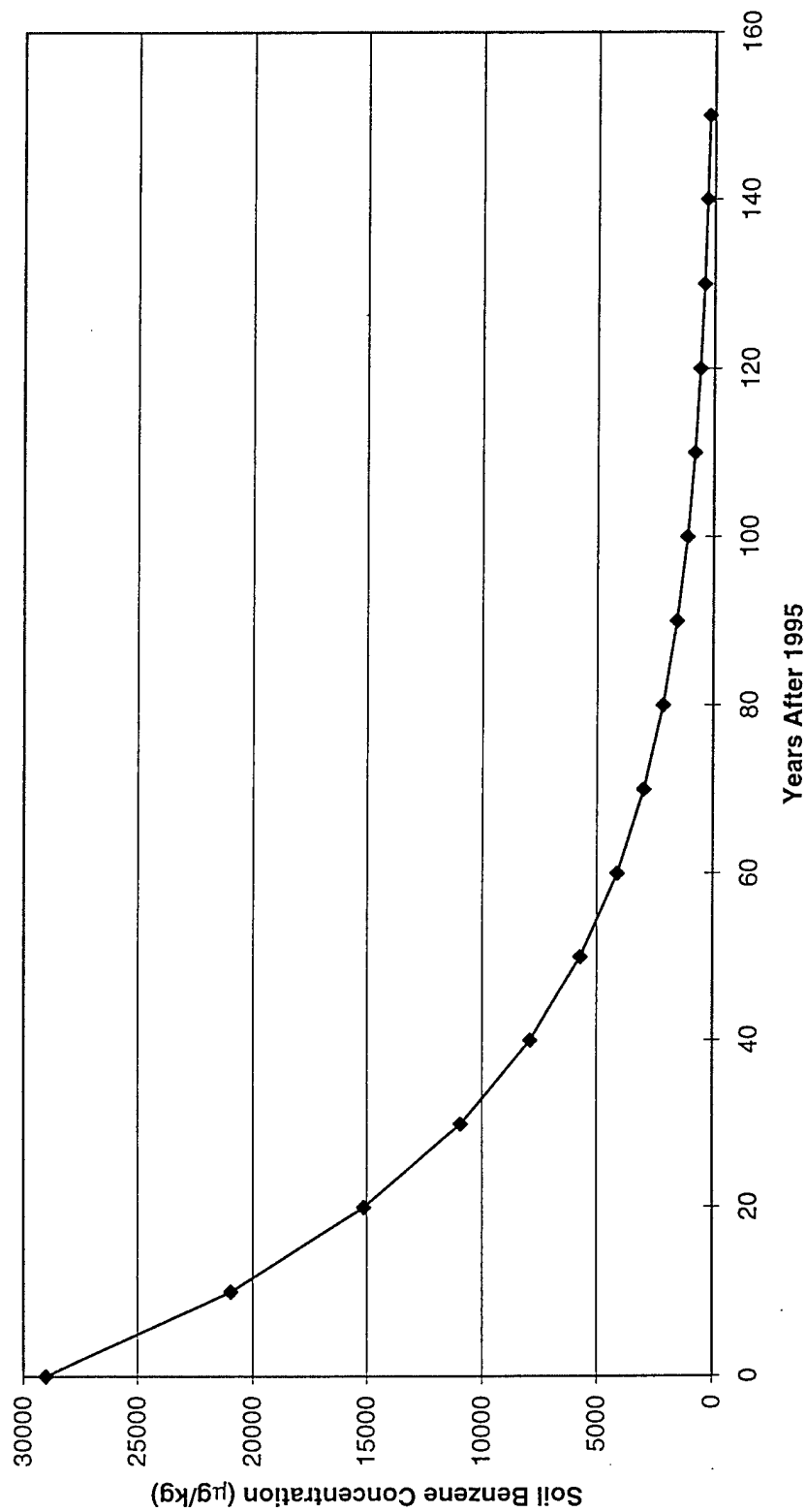
A numerical modeling approach was selected to investigate the fate and transport of an indicator COPC (benzene) at the MOGAS site. Although benzene is not the only groundwater COPC that exceeded its Tier 1 direct contact RBSLs (toluene, ethylbenzene, xylenes, naphthalene, 1,2,4-TMB, and 1,3,5-TMB also exceeded their Tier 1 RBSL), this compound was selected for modeling because it has the most stringent RBSLs, and therefore will likely be the primary "risk-driver" at this site. The mathematical model Bioplume II was used to simulate the behavior of benzene in groundwater at the site over time. The two primary objectives of this modeling effort were to determine the length of time that benzene will be present in site groundwater at concentrations exceeding potential target cleanup levels (Tier 1 RBSLs and/or Tier 2 SSTLs) if engineered remediation is not implemented, and to simulate the degree to which engineered remediation will reduce dissolved benzene concentrations in groundwater and prohibit benzene discharge to the drainage ditch. The mathematical model developed for this effort accounts for the natural physical, chemical, and biological processes documented to be occurring at the MOGAS site. This type of model is useful in defining and understanding the various factors that may contribute most to potential future receptor exposure to site-related contamination (USEPA, 1992).

The Bioplume II model code incorporates advection, dispersion, adsorption, and biodegradation to simulate contaminant migration and degradation. When available, site-specific hydraulic and geochemical conditions were used in the model to simulate

**TABLE 6.3**  
**BATCH FLUSHING MODEL RESULTS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Pore Volume	Years	Benzene Soil Concentration (µg/kg)	Pore Volume	Years	Benzene Soil Concentration (µg/kg)
0	0	29000	36	180	83
1	5	24650	37	185	71
2	10	20953	38	190	60
3	15	17810	39	195	51
4	20	15138	40	200	44
5	25	12867	41	205	37
6	30	10937	42	210	31
7	35	9297	43	215	27
8	40	7902	44	220	23
9	45	6717	45	225	19
10	50	5709	46	230	16
11	55	4853	47	235	14
12	60	4125	48	240	12
13	65	3506	49	245	10
14	70	2980	50	250	9
15	75	2533	51	255	7
16	80	2153	52	260	6
17	85	1830	53	265	5
18	90	1556	54	270	4
19	95	1322	55	275	4
20	100	1124	56	280	3
21	105	955	57	285	3
22	110	812	58	290	2
23	115	690	59	295	2
24	120	587	60	300	2
25	125	499	61	305	1
26	130	424	62	310	1
27	135	360	63	315	1
28	140	306	64	320	1
29	145	260	65	325	1
30	150	221	66	330	1
31	155	188	67	335	1
32	160	160	68	340	0
33	165	136			
34	170	116			
35	175	98			

Note: Model uses a  $K_d$  value of 1.0 (Appendix F) and starts with the maximum soil benzene concentration detected in 1993-1995 (VENT-02, 11-13 feet bgs).



**FIGURE 6.7**

**SOIL BENZENE LEACHING RATE  
BASED ON BATCH FLUSHING MODEL**

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**  
Denver, Colorado

nondestructive contaminant attenuation and transport mechanisms. Where site-specific measurements were unavailable, accepted literature values were substituted. The biodegradation rate constant for benzene described earlier ( $0.0004 \text{ day}^{-1}$ ) was used as the model degradation coefficient to simulate the effects of aerobic and anaerobic biological processes on contaminant fate over time. The Bioplume II model also included a continuing benzene source at the MOGAS site. A more complete description of the Bioplume II model and a detailed discussion of modeling assumptions and calibration procedures are included in Appendix F.

Part of the modeling strategy for this site was to identify and develop a groundwater flow and contaminant transport model that can be used to reasonably simulate observed site conditions. Model calibration is an essential step toward developing an appropriate and defensible mathematical tool to predict contaminant behavior in a complex system (Freeze and Cherry, 1979; Anderson and Woessner, 1992). Model calibration is the process of systematically adjusting specific model input parameters within an expected range until the resulting model output is a reasonably good match to actual field data. A detailed discussion of the groundwater flow and solute transport calibration is provided in Appendix F. The model for the MOGAS site was calibrated by varying the benzene loading rate until simulated dissolved benzene concentrations resembled measured concentrations to a reasonable degree. The calibration of the Bioplume II model developed for the MOGAS site can be evaluated by comparing how closely model predictions match recorded site conditions in terms of groundwater hydraulics and contaminant plume shape, extent, and concentration. The model assumes that the contaminant plume discharges to the southern drainage ditch, and that plume underflow beneath the ditch does not occur. Figure F.1 in Appendix F illustrates both the observed plume in 1995 and the calibrated plume and indicates that the calibrated Bioplume II model is a reasonable estimate of actual field conditions, and is sufficient to use to develop predictive chemical fate estimates.

To predict the future fate and transport of dissolved benzene at the MOGAS site, two Bioplume II model simulations were performed. The first simulation, termed "MOGAS\_1", assumed that the rate at which benzene was introduced into the aquifer geometrically decreased by 3 percent per year (injected benzene concentrations were decreased by 3 percent from the concentration used for the previous year to account for natural weathering of fuel residuals). The source decay rate includes the combined effects of volatilization, dissolution (i.e., leaching), and biodegradation on source area residual LNAPL and sorbed soil contamination. This weathering rate is based on the results of the equilibrium batch flushing model described in Section 6.6.2. The derivation is explained in Appendix F. This model was run for a period of 200 years beyond 1995.

The second simulation, termed "MOGAS\_2", assumes that all of the residual LNAPL in site soils is actively remediated via bioventing for 3 years, at the end of which the source area is no longer contributing benzene to the groundwater. Bioventing is an *in situ* processes in which low-flow air injection is used to enhance the aerobic biodegradation of organic contaminants in vadose zone soils by supplying oxygen to indigenous microbes. In this scenario, bioventing is assumed to commence in 1997. The model assumes a 50 percent reduction in benzene source concentrations

by the end of year 1, a 95 percent reduction by the end of year 2, and complete elimination of the benzene source term by the end of year 3. It should be noted that a bioventing system at the MOGAS site would have only a seasonal impact on deeper contaminated soils in the capillary fringe or below the average water table. Operation of the bioventing system during one or more low-water periods when these soils are drained would be required. As a result, the actual benzene source removal rate may vary depending on groundwater levels.

In addition to bioventing, the effects of a 64-foot-long air sparging curtain downgradient from each of the former UST locations near the drainage ditch was simulated in model MOGAS\_2 by adding oxygen to the groundwater in each of 4 adjacent model cells. The objective of the air sparging curtain simulation was to assess the degree to which benzene discharge to the drainage ditch would be reduced. The air sparging curtain was "turned on" in model MOGAS\_2 for a period of 9 years following 1997, and the model was run for a total of 16 years beyond 1995. Input and output files for each simulation are provided in Appendix F. The model results of MOGAS\_2 are discussed in Section 9, where the effectiveness of remedial approaches involving source reduction technologies is compared to a remedial approach based on natural chemical attenuation processes only.

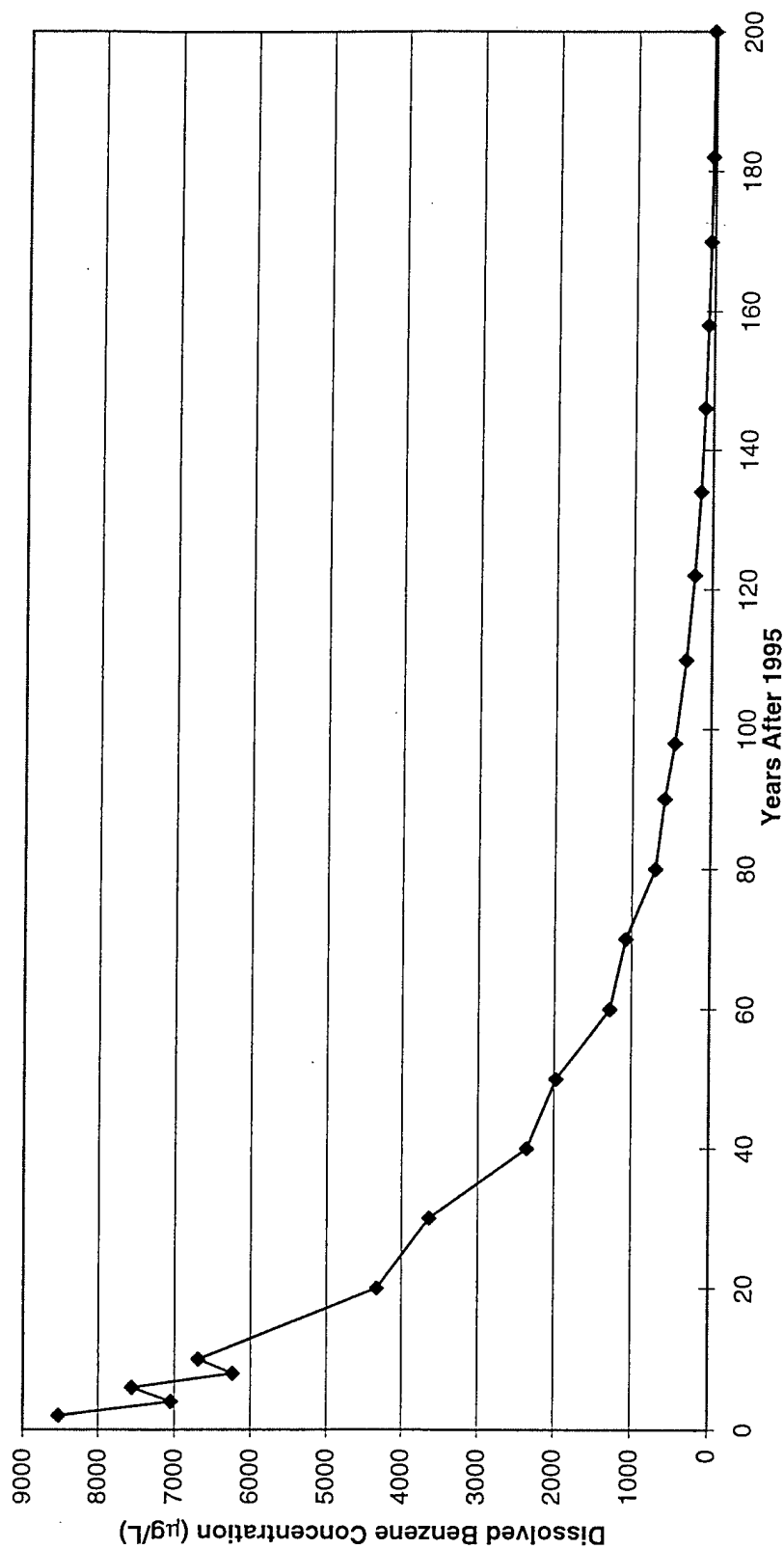
Model MOGAS\_1 predicts that the maximum concentration of benzene in groundwater will not decrease to less than 5 µg/L for approximately 200 years without implementation of an engineered remedial action. As shown on Figure 6.8, the maximum concentration of benzene discharging to the drainage ditch also is predicted to be greater than 5 µg/L for approximately 200 years. Benzene plume maps for calendar years 2048, 2096, and 2147 are shown on Figure 6.9. These maps show that the areal extent of the benzene plume is predicted to remain relatively stable throughout time, although the benzene concentrations within the plume will slowly decrease.

Model MOGAS\_1 is believed to be conservative, and the actual diminishment of the benzene plume may exceed that predicted by the model. However, the model results do indicate that the time frame for remediation of the site to concentrations below potential target cleanup levels under the influence of natural chemical attenuation processes alone will be excessive.

## 6.7 CONCLUSIONS

This section has focused on explaining how and why COPC compounds in impacted media at the MOGAS site are being naturally attenuated. The important findings of this section are summarized below:

- COPCs are biodegrading in saturated soils and groundwater at the MOGAS site primarily via sulfate reduction and methanogenesis;
- The biodegradation rate constant for benzene applied to this site was lower than values typically reported in the technical literature;



**FIGURE 6.8**  
**SIMULATED MAXIMUM BENZENE**  
**CONCENTRATIONS AT**  
**DRAINAGE DITCH**  
**NATURAL ATTENUATION ONLY**

MOGAS Site Corrective Action Plan  
 Risk-Based Approach to Remediation  
 Myrtle Beach AFB, South Carolina

**PARSONS**  
**ENGINEERING SCIENCE, INC.**

Denver, Colorado

- A conservative batch flushing model predicts that maximum benzene concentrations in saturated soils at the MOGAS site will not be reduced by physical leaching processes to concentrations below 100 µg/kg for 170 years;
- A conservative Bioplume II model predicts that benzene concentrations in onsite groundwater will not be reduced to below 5 µg/L by natural chemical attenuation processes for approximately 200 years; and
- The time required to achieve Tier 1 RBSLs for other COPCs at the MOGAS site should be similar to or shorter than that predicted for benzene.

## SECTION 7

### TIER 2 ANALYSIS AND IDENTIFICATION OF FINAL CHEMICALS OF CONCERN

#### 7.1 SUMMARY OF THE TIER 2 EVALUATION

The Tier 1 analysis conducted for this CAP (Section 4) identified benzene, toluene, ethylbenzene, naphthalene, chlorobenzene, and 1,3,5-TMB as potential leachate COPCs in soils; the BTEX compounds, naphthalene, 1,2,4- and 1,3,5-TMB as COPCs in groundwater; the BTEX compounds as COPCs in air; and benzene as a COPC in surface water. These analytes were then evaluated in detail to better define/assess the potential adverse health effects they may cause in current or future human receptors.

In summary, the Tier 2 evaluation concludes that several groundwater COPCs (i.e., benzene, ethylbenzene, and naphthalene) and the surface water COPC (i.e., benzene) will persist in onsite media at concentrations above their matrix-specific, health-protective Tier 2 SSTLs for many years unless some form of engineered remediation is completed at the site. The Tier 2 evaluation also indicates that residual concentrations of soil COPCs are not sufficient to result in leachate at concentrations above the health-protective Tier 2 groundwater SSTLs, although soil contaminants are expected to continue to leach from soil and dissolve into underlying groundwater at low concentrations for many years. Consequently, the Tier 2 evaluation identifies the need to undertake some form of corrective action at the MOGAS site to prevent unacceptable human exposure to contaminated groundwater and surface water. The following sections present the Tier 2 evaluation process for this site in more detail.

#### 7.2 OVERVIEW OF THE TIER 2 PROCESS

The Tier 1 screening process is considered protective of human health because the Tier 1 risk-based screening criteria are based on conservative "reasonable maximum exposure" (RME) assumptions. As stated in Section 4, the Tier 1 screening criteria are defined by SCDHEC (1995) and USEPA (1996) as nonsite-specific or generic risk-based screening levels. However, analytes identified as COPCs in Section 4 of this CAP (i.e., analytes with representative site concentrations exceeding Tier 1 RBSLs) should not automatically be considered to be present at the MOGAS site at levels that pose unacceptable threats to human health. Rather, these exceedances of the generic screening criteria indicate that further evaluation under more site-specific exposure scenarios is warranted. Consequently, a Tier 2 evaluation was deemed necessary to assess whether the presence of various analytes at concentrations above the applicable generic RBSLs presents an unacceptable health threat requiring interim action and/or

prompts the need for final corrective actions that can achieve the desired level of risk reduction at the site in a reasonable time period.

The Tier 2 evaluation consists of three steps (SCDHEC, 1995):

- Establishing a receptor exposure point(s);
- Establishing monitoring requirements and/or site-specific POCs; and
- Calculating the corresponding risk-based SSTL for the COPCs applicable in the source area based on the measured and predicted attenuation of the COPCs away from the source area.

Not explicitly discussed in the SCDHEC (1995) guidance is the importance of reevaluating exposure pathway completion during the Tier 2 evaluation. The revised conceptual site model (CSM) for the MOGAS site, which is presented in Section 7.3, identifies only those receptors and exposure pathways that realistically may be completed under actual current or hypothetical future exposure scenarios, considering land uses and the results of the chemical fate and transport assessment presented in Section 6. The revised CSM is used to guide the completion of the three steps of the Tier 2 evaluation.

Section 6 presented the results of fate and transport modeling used to predict the attenuation of the COPCs migrating away from the source area. The results of this quantitative chemical fate assessment can be incorporated into the revised CSM to help develop Tier 2 SSTLs for the MOGAS site. The risk-based tiered approach is culminated in this section by comparing appropriate site concentrations (observed current, and if appropriate, predicted future) to realistic, matrix-specific SSTLs at receptor exposure points (e.g., at the source area or some distance downgradient or downstream from the source). These SSTLs are described by SCDHEC (1995) as the Tier 2 risk-based criteria, and differ from the generic RBSLs in that the conservative exposure assumptions used to derive the generic RBSLs (e.g., exposure duration of 25 years) are replaced with more realistic site-specific exposure assumptions (e.g., exposure duration of 1 year). It is important to emphasize that the Tier 2 SSTLs are based on achieving levels of human health protection identical to those defined by the generic RBSLs (i.e., the site-specific criteria are based on a carcinogenic target risk limit of  $10^{-6}$  and a noncarcinogenic hazard quotient of  $\leq 1$ ), and are considered adequately conservative and consistent with SCDHEC (1995) and USEPA (1996) recommended practices. These Tier 2 SSTLs may be negotiated as the alternate cleanup goals for the MOGAS site if it is determined that attainment of the generic cleanup criteria is not appropriate, feasible, or cost effective. The SSTLs also can be used to confirm that no unacceptable exposures are likely to occur at the MOGAS site until either site-specific or generic cleanup criteria can be attained, either through engineered remediation or natural chemical attenuation processes.

One of the primary site-specific considerations that can be incorporated into development of the SSTLs is the demonstrated and predicted degree of attenuation of COPCs in affected environmental media. As mentioned above, the comprehensive

chemical fate assessment, which emphasizes documenting bioattenuation of the COPCs, concluded that many natural chemical attenuation processes are operational at this site, but that significant reductions in COPC mass, mobility, and toxicity may not be attained within a reasonable time frame. As discussed in Section 6.6.2, the conservative models predict that, without some type of engineered remediation of subsurface sources, onsite contaminated soils and groundwater could act as a significant source of contaminant mass for many years. Additional engineered remediation may have to be implemented to prevent the continued release of contaminated groundwater to the ditch and to promote reductions of contaminant mass and toxicity in impacted media within a reasonable time frame.

In addition to incorporating engineered approaches into the final corrective action for this site, active remediation measures such as bioventing and air sparging may need to be considered as interim actions, as required by SCDHEC (1995), to prevent any potential imminent, unacceptable exposures that could occur at or near the source area. Pilot testing of various source reduction technologies was completed at this site in anticipation of the need for engineered remediation of subsurface sources. These pilot tests may be defined as interim actions, as testing of these technologies may have mitigated any potential imminent threats. Section 8 describes the outcome of the completed and ongoing pilot tests for each of the source reduction technologies.

In summary, the objectives of developing Tier 2 SSTLs that include exposure assumptions more representative of actual site conditions are: 1) to determine whether current or predicted future site concentrations of COPCs present an unacceptable risk to current and future receptors in the absence of engineered remediation other than interim action (given the type and nature of exposures likely to occur near the source area); and 2) to provide a mechanism or reference to assess the cost and time required to lower site concentrations to achieve adequate risk reduction at the site.

The impact of natural chemical attenuation processes on COPC concentrations at potential exposure points and realistic assumptions about likely exposure routes were incorporated into the SSTLs. If current and predicted future site concentrations are below the SSTLs, natural chemical attenuation supplemented with land use controls and long-term monitoring would afford the desired level of protectiveness (i.e., carcinogenic and noncarcinogenic risks would be below the threshold risk levels established by SCDHEC and USEPA). If the current or predicted future site concentrations exceed the SSTLs, more active remediation techniques such as engineered groundwater/soil remediation to supplement natural chemical attenuation processes would be considered. Thus, the SSTLs may be considered as proposed alternate cleanup criteria for the MOGAS site.

### **7.3 REVISED CONCEPTUAL SITE MODEL REVIEW**

The preliminary CSM presented in Section 4 was used to qualitatively identify potential human and ecological receptors that may be exposed to site-related contaminants, and to define the types of these potential exposures to contaminants at and migrating from the MOGAS site (Figure 4.2). The preliminary CSM describes onsite release points, the affected physical media, the types of contaminant transport

and fate mechanisms that may be involved at the site, each group of potentially exposed populations or receptors, and how each receptor group could come into contact with site-related contamination. This CSM was used to identify which of the exposure assumptions used to develop generic cleanup criteria most closely approximates site conditions. The exposure assumptions incorporated into the generic RBSLs were identified as generally representative of the types of exposure that could occur at the MOGAS site, but greatly overestimated the magnitude of exposure specific to current and expected future site conditions. In some cases, exposure pathways identified in the preliminary CSM were not necessarily realistic, but were included in the Tier 1 evaluation to be conservative. The preliminary CSM exposure pathways are re-evaluated in this section using more reasonable land use assumptions and the Tier 2 chemical fate information presented in Section 6. It is important to emphasize that the purpose of using the preliminary CSM and the conservative, nonsite-specific RBSLs to identify COPCs was to ensure that all subsequent assessment activities beyond the Tier 1 screening evaluation address the full range of contaminants that may require some type of remediation.

As mentioned earlier in Section 7.1, the revised CSM for the MOGAS site, which is presented in Figure 7.1 and briefly reviewed in the following subsections, identifies only those receptors and exposure pathways that realistically may be involved in actual current or hypothetical future exposures. The outcome of the chemical fate assessment presented in Section 6 and the types of exposures likely to occur at this industrial site are reflected in this revised CSM. Justification for each site-specific exposure assumption is provided in subsequent discussions.

### **7.3.1 Revised Conceptual Model**

#### **7.3.1.1 Sources, Affected Media, Release Mechanisms, and Contaminant Environmental Transport**

The likelihood of release from a source, the nature of the contaminants involved, the affected environmental media, and the probable magnitude of their release all are included in the revised CSM (Figure 7.1). As described in Section 1.3.1, the most likely sources of site-related chemical contamination are the USTs previously used to store motor gasoline (MOGAS) and possibly diesel fuel. Historical releases from leaking USTs have contaminated site soil and groundwater with fuel hydrocarbons. In 1993, the USTs and associated delivery lines were excavated, but the majority of the contaminated soils were left in place.

The predominant ongoing release mechanisms for air and groundwater COPCs are volatilization and leaching from contaminated soils. Simple equilibrium partitioning equations and soil gas sampling data were used to assess the potential for subsurface sources to contribute significant VOC mass to indoor or outdoor breathing zones. As discussed in Section 6.6.1, volatilization from subsurface sources could theoretically result in outdoor ambient air concentrations above Tier 1 RBSLs if the asphalt cover is disturbed or removed as part of future land use plans. Based on simple equilibrium partitioning calculations using soil gas data collected before pilot testing source reduction technologies (See Table 6.2), benzene and toluene concentrations in ambient

air for outdoor workers could exceed the stringent Tier 1 air RBSL by approximately three orders of magnitude. However, because no air COPC concentrations for indoor or outdoor workers would exceed the 1989 PELs, this potential exposure pathway would be considered insignificant if completed. No air COPC is predicted to migrate into indoor breathing zones at concentrations above the stringent Tier 1 RBSLs (SCDHEC, 1995).

Conservative leaching estimates presented in Section 6 indicated that leaching from onsite contaminated soils is expected to be a significant release mechanism to groundwater for about 150 to 200 years (i.e., through the year 2095). Although only minimal downgradient migration of contaminants is possible because the southern drainage ditch intercepts the plume (Figure 6.10), the rate of biodegradation of dissolved COPCs is generally reduced in groundwater because of the absence of a sufficient influx of electron acceptors into the plume core. As the field data show, the degradation rates are not sufficient to limit surface water contamination. However, increased degradation at the groundwater-surface water interface and within aerated surface water is expected.

#### **7.3.1.2 Potentially Exposed Receptors, Exposure Points, and Exposure Routes**

The revised CSM for the MOGAS site also refines the identification of potentially exposed receptor populations, receptor exposure points, and exposure routes for realistic scenarios based on specific site conditions. These components better reflect the likelihood and extent of human or ecological receptor contact with site-related contaminants. As described in Section 3, the MOGAS site is highly industrialized, with both fenced and non-fenced portions. In the fenced area of the MOGAS site, there are several former office buildings, the former motorpool, several storage facilities, and a vehicle wash rack. The fenced area is completely covered with asphalt pavement. Outside the fence, the remainder of the MOGAS site is vegetated with grass and wooded areas. In addition to this vegetated area, an intermittent drainage ditch borders the site outside the fenced area to the east.

As stated in Section 3.6.2, the ultimate cleanup goal for the MOGAS site is to restore the site to a condition suitable for unrestricted use, which is the long-term plan for this site. However, the primary short-term cleanup goal for the MOGAS site (and the objective of this risk-based CAP) is to restore the site to a status suitable for commercial/industrial use, which is the planned near-term use of the site. Therefore, the potentially exposed receptors, exposure points, and exposure routes identified in this section are those that are consistent with commercial/industrial use of the site.

Using the most conservative exposure assumptions appropriate for the MOGAS site, the only realistic human receptors that are likely to become exposed to contaminants at the MOGAS site in the near-term is the onsite intrusive worker involved in demolition, removal, and/or construction activities and trespassers/recreators coming in contact with contaminated surface water and sediment in the ditch just south of the MOGAS site. The activities of onsite nonintrusive workers are generally confined to the paved areas of the site, and even incidental contact with contaminated environmental media is unlikely. No exposure of current onsite nonintrusive workers to these contaminated

site media is occurring or is likely to occur in the future. Furthermore, the industrial nature of the site, which includes concrete and asphalt driveways and parking areas, motorpool facilities, office buildings, and chain link fencing to limit access, precludes the existence of suitable onsite wildlife habitat. No resident ecological receptors were identified for which soils and/or groundwater are likely contaminant exposure media. Aquatic organisms living in and along the drainage ditch south of the site could be exposed to contaminants discharged into the surface water. However, surface water COPC concentrations are below ecological RBSLs (i.e., below state aquatic life surface water quality standards). Other than potential exposure of onsite recreators/trespassers that come into contact with impacted surface water and drainage ditch soil/sediment, no exposure pathways involving potential offsite human receptors are or will be complete.

Additionally, worker exposure to groundwater is re-examined in this Tier 2 evaluation because maximum groundwater concentrations exceed ingestion-based RBSLs. Incidental ingestion of groundwater by the onsite intrusive worker was eliminated as a reasonable exposure route. It is not reasonable to assume that intrusive workers could actually consume (even incidentally) a significant amount of contaminated groundwater during short-term excavation activities. Instead, onsite workers engaging in intrusive activities could come into direct dermal contact with contaminated groundwater. This exposure pathway, rather than an exposure pathway including incidental ingestion (the basis of the Tier 1 RBSLs), will be used to define the health-protective Tier 2 SSTLs for groundwater. Similarly to the Tier 1 evaluation, the soil leaching SSTLs that prevent generation of leachate above the Tier 2 groundwater SSTLs will be "back calculated" from these groundwater SSTLs.

Another completed exposure pathway also could exist between recreators/trespassers and contaminated surface water and drainage ditch soil/sediment at the MOGAS site. As the Base has become more commercialized with non-Air Force agencies, the MOGAS site vicinity, especially the ditch, has become more accessible to trespassers/recreators. A conservative but plausible exposure scenario is that of a child wading in the ditch near the MOGAS site, during the spring, summer, and fall months, collecting plants and animals indigenous to the ditch. Incidental ingestion of surface water and incidental dermal exposure to surface water and sediment are reasonable exposure routes that could be involved in potentially completed exposure pathways at the MOGAS site. These exposure pathways will be factored into the development of health-protective Tier 2 SSTLs for surface water and sediment.

Finally, inhalation of VOCs (partitioning from either contaminated soil or groundwater) in ambient air at the site theoretically also could result in a completed pathway for the onsite intrusive worker should the asphalt pavement be disturbed or removed. The equilibrium partitioning calculations based on soil gas concentrations measured prior to pilot testing source reduction technologies, which are presented in Section 6, suggest that subsurface sources could result in breathing-zone air concentrations above the Tier 1 RBSLs but below the 1989 OSHA PELs. Because these calculations do not account for the asphalt pavement, which is limiting volatilization from subsurface media, this exposure pathway is not likely to be completed unless the asphalt pavement is disturbed or removed. Additionally, this exposure pathway should be considered insignificant even if it is completed in the

future because: 1) predicted exposure-point air concentrations for outdoor workers are below the conservative OSHA (1989) PELs, and 2) the subsurface VOC sources that were used to predict these exposure-point air concentrations have already been appreciably reduced by pilot testing (see Section 8). Consequently, the inhalation route will not be factored into the development of the Tier 2 SSTLs for groundwater and/or soils.

### 7.3.2 Summary of Completed Exposure Pathways

Given the current and planned future uses of the MOGAS site and the outcome of the Tier 2 quantitative chemical fate assessment presented in Section 6, onsite intrusive workers and trespassers/recreators could be exposed to site-related contamination via several exposure pathways (Figure 7.1). The health-based Tier 2 SSTLs developed for the MOGAS site define the residual COPC concentrations in onsite media that will not result in unacceptable carcinogenic risks or noncarcinogenic hazards to hypothetical onsite intrusive workers and trespassers/recreators in the event that they are incidentally exposed to site-related contamination as described by the revised CSM. The groundwater-protective soil SSTLs define the residual concentration at which COPCs can persist in capillary fringe soils and not generate leachate at concentrations equal to or greater than the health-based groundwater SSTLs.

## 7.4 DEVELOPMENT OF SITE-SPECIFIC TARGET LEVELS (SSTLS)

SCDHEC (1995) has not defined an algorithm for dermal contact with chemicals in water. Consequently, the algorithm used to calculate the groundwater SSTLs assuming incidental dermal contact only is based on the general absorption intake equation for dermal contact with chemicals in water developed by USEPA (1989). This algorithm was modified for the surface water SSTL to include incidental ingestion of water, based on the general incidental intake equation developed by USEPA (1989). In addition to the exposure route considered in the SSTL calculation, two other site-specific exposure assumptions (i.e., exposure frequency and exposure duration) were used (see SSTL equations in Appendix G). An RME exposure frequency of 250 days per year was assumed to be reasonably conservative for onsite workers engaged in highly intrusive activities at the MOGAS site, such as the installation of a bioventing and/or biosparging system. The value of 250 days per year is based on a 5-day work week with 2 weeks of vacation each year. An RME exposure frequency of 90 days per year was assumed to be reasonably conservative for onsite recreators/trespassers that may be wading in the ditch. An exposure duration of 1 year was assumed to be a conservative (health-protective) exposure duration for intrusive onsite workers, considering site size and the current and anticipated future operational activities occurring at the MOGAS site. An exposure duration of 9 years was assumed to be conservative for a child/adult recreator/trespasser. All other exposure variables used to calculate the water SSTLs are USEPA (1989 and 1991c) default values.

COPC toxicity values used in the SSTL derivations are based on toxicity data reported in the Integrated Risk Information System (IRIS) (Micromedex, Inc., 1996) or the toxicity data used to derive the generic RBSLs. Appendix G presents the exposure assumptions and derivation of the SSTLs for the MOGAS site.

#### **7.4.1 SSTLs for Soil**

No chemical was detected in soils at concentrations above Tier 1 health-based RBSLs for onsite workers. This means that onsite soils do not present an unacceptable health threat to potential workers. Soil COPCs were identified based on exceedances of Tier 1 soil leaching RBSLs only. Table 7.1 presents the soil leaching SSTLs for each of the soil COPCs for the MOGAS site; Tier 1 soil leaching RBSLs are provided for comparison. The soil leaching SSTL is based on site-specific soil/groundwater partitioning data and an equilibrium partitioning relationship based on contaminant release via rising and falling groundwater table rather than infiltrating precipitation (refer to Section 6.6.2). This approach is different from that used to develop Tier 1 soil leaching RBSLs. The soil leaching RBSLs defined by SCDHEC (1995) are based on a generic dilution/attenuation factor (DAF), which was estimated using a soil leachability model based on an equilibrium sorption/desorption relationship and release via infiltration of precipitation. In contrast to the DAF approach, the soil leaching SSTLs are chemical- and site-specific in terms of how well each chemical is attenuated in site soils (i.e., measured soil data for each chemical species are used, rather than employing a generic DAF that applies to all chemicals and sites). Appendix G presents the simple algorithms used to derive the soil leaching SSTLs. The algorithm is used to "back calculate" the soil leaching SSTLs from desirable groundwater concentrations [i.e., health-based groundwater SSTL (Table 7.2) and the generic industrial RBSL for groundwater] accounting for site- and chemical-specific attenuation/release processes.

#### **7.4.2 SSTLs for Groundwater**

Table 7.2 presents the groundwater SSTLs developed to prevent unacceptable risks to onsite intrusive workers due to incidental dermal exposure to contaminated groundwater; the generic groundwater RBSLs defined by SCDHEC (1995) are provided for comparison. RME and central tendency (CT) SSTLs are presented. The RME SSTLs are designed to illustrate the residual concentration that can persist in onsite groundwater given "high-end" (reasonable maximum) exposure potential, whereas the CT SSTLs better illustrate the residual concentration that can persist in onsite groundwater given mean or average exposure potential. The CT SSTLs are presented for comparative purposes only to provide a less-than-maximum-exposure perspective. As stated earlier, the health-based RBSLs for groundwater are calculated assuming purposeful ingestion of onsite groundwater by onsite workers under residential-type exposure conditions (i.e., 30-year exposure duration, 2 liters per day consumption rate, etc.). Therefore, the health-based RBSLs are provided only as "benchmark" values identifying the risk-based concentrations for which no land and groundwater use restrictions would be necessary.

#### **7.4.3 SSTLs for Surface Water and Sediment**

Table 7.3 presents the health-based surface water RME and CT SSTLs; Tier 1 surface water RBSLs used in the Tier 1 analysis are provided for comparison. SSTLs

**TABLE 7.1**  
**SITE-SPECIFIC TARGET LEVELS FOR SOILS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MRYTLE BEACH AFB, SOUTH CAROLINA**

Soil COPC	Units	Soil Leaching SSTL to Attain RME Health-Based SSTL <sup>a/</sup>	Soil Leaching SSTL to Attain CT Health-Based SSTL <sup>b/</sup>	Soil Leaching SSTL to Attain Tier 1 RBSLs <sup>c/</sup>	Soil Leaching RBSL <sup>d/</sup>
Benzene	mg/kg	4.2	5.6	0.006	0.007
Toluene	mg/kg	2,490	3,307	1.1	1.7
Ethylbenzene	mg/kg	17.5	23.2	4.8	1.5
Naphthalene	mg/kg	12.5	16.5	1.2	0.2
Chlorobenzene	mg/kg	300.7	404.1	36.6	0.48
1,3,5-Trimethylbenzene	mg/kg	309.8	410.3	129.4	0.208

NOTE: Derivation of soil leaching SSTLs presented in Appendix G.

<sup>a/</sup> Site-specific soil leaching SSTL based on partitioning relationship explained in Appendix G (and Section 6) to evaluate long-term leaching of soil COPC mass from soils. Based on site-specific  $K_D$  value, site-specific foc of 0.0014, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = RME health-based groundwater SSTL (worker dermal exposure to groundwater) was used to "back-calculate" groundwater protective SSTL.

<sup>b/</sup> Site-specific soil leaching SSTL based on partitioning relationship explained in Appendix G (and Section 6) to evaluate long-term leaching of soil COPC mass from soils. Based on site-specific  $K_D$  value, site-specific foc of 0.0014, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = CT health-based groundwater SSTL (worker dermal exposure to groundwater) was used to "back-calculate" groundwater protective SSTL.

<sup>c/</sup> Site-specific soil leaching SSTL based on partitioning relationship explained in Appendix G (and Section 6) to evaluate long-term leaching of soil COPC mass from soils. Based on site-specific  $K_D$  value, site-specific foc of 0.0014, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = Tier 1 RBSL for groundwater (worker unrestricted use of groundwater) was used to "back-calculate" groundwater protective SSTL.

<sup>d/</sup> Tier 1 soil leaching RBSLs provided for comparison only.

**TABLE 7.2**  
**SITE-SPECIFIC TARGET LEVELS FOR GROUNDWATER**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MRYTLE BEACH AFB, SOUTH CAROLINA**

COPC	Units	Tier 2 RME Health-Based SSTLs <sup>a/</sup>	Tier 2 CT (Average) Health-Based SSTLs <sup>b/</sup>	Tier 1 SCDHEC/EPA Generic RBSLs <sup>c/</sup>
Benzene	µg/L	241	319	0.36
Ethylbenzene	µg/L	2,530	3,350	700
Toluene	µg/L	8,810	11,700	750
Xylenes	µg/L	49,600	65,600	10,000
Naphthalene	µg/L	255	338	25
1,2,4-Trimethylbenzene	µg/L	718	951	300
1,3,5-Trimethylbenzene	µg/L	718	951	300

NOTE: Derivation of SSTLs presented in Appendix G.

<sup>a/</sup>RME SSTLs are designed to protect onsite intrusive workers from unacceptable exposure due to incidental exposure via dermal contact with dissolved chemicals in groundwater using site-specific exposure assumptions (carcinogenic value for benzene; noncarcinogenic values for all other COPCs).

<sup>b/</sup> Average or CT SSTLs (i.e., SSTLs based on average exposure assumptions) are provided for comparison with RME SSTLs for onsite intrusive workers exposed via incidental dermal contact with dissolved chemicals in groundwater (carcinogenic value for benzene; noncarcinogenic values for all other COPCs).

<sup>c/</sup> SCDHEC (1995)/EPA Region VIII (1996) (the lesser of the two values) generic RBSLs would be protective of onsite workers whose drinking water comes from an onsite groundwater source.

**TABLE 7.3**  
**SITE-SPECIFIC TARGET LEVELS FOR SURFACE WATER AND SEDIMENT**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

COPC	Tier 2 RME Health-Based SSTL		Tier 2 CT Health-Based SSTL		Tier 1 Surface Water RBSL (µg/L) <sup>e/</sup>
	Surface Water (µg/L) <sup>a/</sup>	Sediment (µg/kg) <sup>b/</sup>	Surface Water (µg/L) <sup>c/</sup>	Sediment (µg/kg) <sup>d/</sup>	
Benzene	99.6	26,900	367	253,000	5

NOTE: Derivation of SSTLs presented in Appendix G.

<sup>a/</sup> Site-specific RME surface water SSTL is designed to protect an onsite child/adult (aged 8 to 16) from unacceptable exposure due to incidental dermal contact with and incidental ingestion of dissolved benzene in surface water while trespassing/recreating.

<sup>b/</sup> Site-specific RME sediment SSTL is designed to protect an onsite child/adult (aged 8 to 16) from unacceptable exposure due to incidental dermal contact with benzene in saturated soil/sediment while trespassing/recreating.

<sup>c/</sup> Average or CT SSTL for surface water (i.e., SSTL based on average exposure assumptions) is provided for comparison.

<sup>d/</sup> Average or CT SSTL for sediment (i.e., SSTL based on average exposure assumptions) is provided for comparison.

<sup>e/</sup> Tier 1 health-based surface water RBSL (i.e., the federal MCL for benzene) is provided for comparison.

for surface water and sediment were based on the assumption that a child/adolescent would spend approximately 3 hours per day during the spring, summer, and fall months (i.e., 90 days) wading in the ditch at the MOGAS site. The surface water and sediment RME SSTLs are health-based values calculated to protect these onsite receptors from unacceptable health risks associated with dermal exposure to chemical contamination in surface water and sediment and incidental ingestion of surface water.

## 7.5 COMPARISON OF EXPOSURE-POINT CONCENTRATIONS TO SSTLS

With the exception of average soil COPC values used to represent potential leachate sources, the maximum detected concentrations of groundwater, surface water, and sediment COPCs were conservatively assumed to represent the current and future exposure-point concentrations at the MOGAS site. This is a reasonable, albeit conservative, assumption because the Tier 2 chemical fate assessment (Section 6) suggests that site concentrations are not expected to appreciably decrease (or increase) for many years unless some type of engineered remediation is completed at the site.

Table 7.4 compares the average detected soil COPC concentrations to the soil leaching SSTLs. (Note that this comparison is similar to the Tier 1 evaluation of site average detected soil COPC concentrations compared with generic RBSLs.) None of the average detected soil COPC concentrations exceed the RME soil leaching SSTL, although maximum detected concentrations of benzene, ethylbenzene, and naphthalene exceed their RME soil leaching SSTLs. This means that, although fuel hydrocarbon compounds are expected to continue to slowly leach from soils (Section 6.6.2), the residual concentrations are not sufficient to generate leachate above the health-protective groundwater SSTLs. Measurable impacts on groundwater are to be anticipated, but not at concentrations that result in sustained groundwater concentrations above the groundwater SSTLs.

Table 7.5 compares the maximum detected groundwater COPC concentrations to the health-based groundwater SSTLs. The maximum detected concentration of benzene, ethylbenzene, and naphthalene measured in groundwater in 1995 exceed the health-based groundwater RME and CT SSTLs. Benzene and ethylbenzene exceed their health-based SSTL by more than an order of magnitude. All other groundwater COPCs are below their health-based RME SSTLs. The Bioplume II model results presented in Section 6.6.3 indicate that more than 90 years will be required for natural attenuation processes alone to reduce onsite maximum concentrations of benzene (the indicator COPC) below its health-based SSTL (i.e., below 240 µg/L). During that time (i.e., until about the year 2086), additional contaminant mass will migrate to and discharge into the downgradient ditch.

Table 7.6 compares the maximum detected concentration of benzene measured in surface water and sediment to the health-based surface water and sediment SSTLs. The maximum detected 1995 concentration of benzene in sediment is significantly below RME SSTLs. However, the maximum detected 1995 concentration of benzene in surface water (i.e., 580 µg/L) is above both the RME and CT surface water SSTL. Additionally, the conservative Bioplume II model results presented in Section 6.6.3 suggest that benzene in groundwater at concentrations above the surface water SSTL

**TABLE 7.4**  
**COMPARISON OF ANALYTICAL SOIL DATA TO SOIL LEACHING SSTLS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MRYTLE BEACH AFB, SOUTH CAROLINA**

Soil COPC	Units	Maximum Concentration <sup>a/</sup>	Calculated Average Concentration <sup>b/</sup>	Soil Leaching SSTL to Attain RME Health-Based SSTL <sup>c/</sup>	Soil Leaching SSTL to Attain CT Health-Based SSTL <sup>d/</sup>	Does Avg. Conc. Exceed Most Stringent SSTL?	Does Max. Conc. Exceed Most Stringent SSTL?
Benzene	mg/kg	87	2.86	4.2	5.6	NO	YES
Toluene	mg/kg	650	23.4	2,490	3,307	NO	NO
Ethylbenzene	mg/kg	180	7.2	17.5	23.2	NO	YES
Naphthalene	mg/kg	24	4.4	12.5	16.5	NO	YES
Chlorobenzene	mg/kg	27	1.17	300.7	404.1	NO	NO
1,3,5-Trimethylbenzene	mg/kg	220	8.3	309.8	410.3	NO	NO

NOTE: Derivation of soil leaching SSTLS presented in Appendix G.

<sup>a/</sup> Maximum soil concentrations were obtained from the 1995 risk-based investigation sampling events.

<sup>b/</sup> Calculated average soil concentrations were obtained from the 1995 risk-based investigation sampling events.

<sup>c/</sup> Site-specific soil leaching SSTL based on partitioning relationship explained in Appendix G (and Section 6) to evaluate long-term leaching of soil COPC mass from soils. Based on site-specific  $K_D$  value, site-specific  $foc$  of 0.0014, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = RME health-based groundwater SSTL (worker dermal exposure to groundwater) was used to "back-calculate" groundwater protective SSTL.

<sup>d/</sup> Site-specific soil leaching SSTL based on partitioning relationship explained in Appendix G (and Section 6) to evaluate long-term leaching of soil COPC mass from soils. Based on site-specific  $K_D$  value, site-specific  $foc$  of 0.0014, and simple equilibrium partitioning model used to simulate observed site conditions. Target groundwater concentration = CT health-based groundwater SSTL (worker dermal exposure to groundwater) was used to "back-calculate" groundwater protective SSTL.

**TABLE 7.5**  
**COMPARISON OF ANALYTICAL GROUNDWATER DATA TO SITE-SPECIFIC TARGET LEVELS**  
**MOGAS CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MRYTLE BEACH AFB, SOUTH CAROLINA**

COPC	Units	Detected Site Maximum Concentration <sup>a/</sup>	Tier 2 RME Health-Based SSTLs <sup>b/</sup>	Tier 2 CT (Average) Exposure Health- Based SSTLs <sup>c/</sup>	Tier 1 SCDHEC/EPA Generic RBSLs <sup>d/</sup>	Does Detected Site Maximum Concentration Exceed RME SSTL?	If "YES," Does Detected Site Maximum Concentration Exceed CT SSTL?
Benzene	µg/L	5,000	241	319	0.36	YES	YES
Ethylbenzene	µg/L	26,000	2,530	3,350	700	YES	YES
Toluene	µg/L	2,300	8,810	11,700	750	NO	-
Xylenes	µg/L	14,000	49,600	65,600	10,000	NO	-
Naphthalene	µg/L	490	255	338	25	YES	YES
Chlorobenzene	µg/L	29	718	951	300	NO	-
1,3,5-Trimethylbenzene	µg/L	510	718	951	300	NO	-

7-15

NOTE: Derivation of SSTLs presented in Appendix G.

<sup>a/</sup> Maximum concentrations were obtained from the 1995 risk-based investigation sampling events.

<sup>b/</sup> RME SSTLs are designed to protect onsite intrusive workers from unacceptable exposure due to incidental exposure via dermal contact with dissolved chemicals in groundwater using site-specific exposure assumptions (carcinogenic value for benzene; noncarcinogenic values for all other COPCs).

<sup>c/</sup> Average or CT SSTLs (i.e., SSTLs based on average exposure assumptions) are provided for comparison with RME SSTLs for onsite intrusive workers exposed via incidental dermal contact with dissolved chemicals in groundwater (carcinogenic value for benzene; noncarcinogenic values for all other COPCs).

<sup>d/</sup> SCDHEC (1995)/EPA Region VIII (1996) (the lesser of the two values) generic RBSLs would be protective of onsite workers whose drinking water comes from an onsite groundwater source.

**TABLE 7.6**  
**COMPARISON OF ANALYTICAL SURFACE WATER AND SEDIMENT DATA TO SITE-SPECIFIC TARGET LEVELS**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

COPC	Detected Site Surface Water Maximum Concentration (µg/L) <sup>a/</sup>	Detected Site Sediment Maximum Concentration (µg/kg) <sup>b/</sup>	Tier 2 RME Health-Based SSTL		Tier 2 CT Health-Based SSTL		Does Detected Site Surface Water Max. Concentration Exceed Most Stringent SSTL?		Does Detected Site Sediment Max. Concentration Exceed Most Stringent SSTL?	
			Surface Water (µg/L) <sup>c/</sup>	Sediment (µg/kg) <sup>d/</sup>	Surface Water (µg/L) <sup>e/</sup>	Sediment (µg/kg) <sup>f/</sup>				
Benzene	580	6,300	100	26,900	367	253,000	YES		NO	

NOTE: Derivation of SSTLs presented in Appendix G.

<sup>a/</sup> Maximum surface water benzene concentration was obtained from the 1995 risk-based investigation sampling events.

<sup>b/</sup> Maximum sediment benzene concentration was obtained from the 1995 risk-based investigation sampling events.

<sup>c/</sup> Site-specific RME surface water SSTL is designed to protect an onsite child/adult (aged 8 to 16) from unacceptable exposure due to incidental dermal contact with and incidental ingestion of dissolved benzene in surface water while trespassing/recreating.

<sup>d/</sup> Site-specific RME sediment SSTL is designed to protect an onsite child/adult (aged 8 to 16) from unacceptable exposure due to incidental dermal contact with benzene in saturated soil/sediment while trespassing/recreating.

<sup>e/</sup> Average or CT SSTL for surface water (i.e., SSTL based on average exposure assumptions) is provided for comparison.

<sup>f/</sup> Average or CT SSTL for sediment (i.e., SSTL based on average exposure assumptions) is provided for comparison.

could continue to discharge into the ditch for about 110 more years (i.e., year 2105). After that time, natural chemical attenuation processes in the source area will be sufficient to minimize benzene concentrations in groundwater discharges below the surface water SSTL.

It is important to note that the Bioplume II model was not developed to estimate surface water exposure-point concentrations. The attenuation processes that are operating between the point of contaminated groundwater discharge to surface water and downgradient sampling locations have not been factored into the modeling effort. Rather, the Bioplume II model results are useful only in estimating whether continued discharges of contaminated groundwater to surface water could potentially occur. The operant chemical attenuation processes in surface water are obviously significant, as the benzene concentration predicted to be now discharging into the ditch is much less than detected in 1995. Therefore, it is conceivable that adverse impacts on surface water could continue over time (based on the conservative Bioplume II model results).

## **7.6 SUMMARY OF RISK REDUCTION REQUIREMENTS**

Comparison of detected COPC concentrations to SSTLs indicates that some type of engineered remediation may be necessary to achieve health-based groundwater and surface water SSTLs and to limit contaminated groundwater discharge to downgradient surface water within a reasonable time frame. Natural chemical attenuation processes are not sufficient to achieve groundwater SSTLs, or perhaps to minimize discharges to surface water, within the next 90 to 110 years. Therefore, if any exposure pathway involving either onsite workers or possibly onsite recreators/trespassers is completed during this time, these receptors could be exposed to residual COPC concentrations that present an unacceptable health risk.

Consequently, some type of remediation approach that supplements natural chemical attenuation processes within groundwater and reduces the potential discharge of contaminated groundwater to surface is warranted. The Air Force intends to base long-term cleanup objectives on the health-protective SSTLs, rather than to pursue compliance with Tier 1 RBSLs. These cleanup objectives will provide an adequate level of health protection in the event that current or hypothetical future receptors are exposed to contaminated media, given the land use and likelihood/nature of exposure. Section 8 describes the effectiveness of various low-cost source reduction technologies that have been tested at this and other similar sites; Section 9 describes the most cost-effective corrective action for attaining the health-protective SSTLs in a reasonable time frame.

## **7.7 SITE PRIORITY CLASSIFICATION AND TIER 2 ACTION DECISION**

Based upon the Tier 2 assessment and evaluation, the MOGAS site remains classified as a Category 5 release. Although COPCs are expected to persist in groundwater and surface water at concentrations above the health-protective SSTLs for many years without some form of engineered remediation, a Category 5 classification is warranted because exposure pathways are complete. The SSTLs were developed assuming that only onsite workers and recreators/trespassers in the southern ditch could

be exposed to contaminated soils, groundwater, and/or surface water/sediments. The presence of the asphalt paving, the lack of intrusive activities, and the unlikelihood that recreators/trespassers will be present in the ditch where elevated benzene concentrations persist minimize the potential for unacceptable exposure.

However, because residual concentrations of COPCs will persist in groundwater and surface water above the health-protective SSTLs and contaminated groundwater could continue to discharge to surface water at COPC concentrations above surface water SSTLs for more than 100 years, some type of engineered remediation is warranted. The remaining sections of this CAP focus on developing a cost-effective corrective action approach to uniformly achieve health-protective SSTLs and prevent unacceptable discharges to surface water within a reasonable time frame.

## SECTION 8

### PILOT TESTING OF SOURCE REDUCTION TECHNOLOGIES

Selected source reduction technologies were field-tested at the MOGAS site in the event that engineered source removal is required either to protect human health and the environment or to reduce the total time and cost of remediation. A partial *in situ* bioventing pilot test was performed on November 15 and 16, 1995, and an SVE pilot test was performed from October 1995 to January 1996 to determine the effectiveness of these remedial techniques in treating site-related contamination. Results from these tests are summarized in the following sections. Test data are presented in tabular form in Appendix H.

#### 8.1 *IN SITU* BIOVENTING PILOT TESTING

##### 8.1.1 Vapor Monitoring Point Installation

Eight vapor monitoring points (SV-01 through SV-08) were installed during the Phase I and II field programs in January and August 1995, respectively (Figure 2.2). These points are screened in the sand and silty sand zones overlying the water table in the 5- to 10-foot-bgs depth interval (Figures 3.2 and 3.3). Installation details for these points are described in Section 2.2.1 and 2.3.2, and borehole logs and well construction diagrams for the vapor monitoring points are included in Appendix C.

Vapor monitoring points SV-01 through SV-04 are constructed of 0.75-inch-diameter PVC casing and screen. The screens are 3 feet long and factory slotted with 0.010-inch openings. Each of these points is screened between 4 and 8 feet bgs. Vapor monitoring points SV-05 through SV-08 are similarly constructed, with 5-foot-long, factory-slotted screens with 0.01-inch openings. Each of these points is screened from 5 to 10 feet bgs.

##### 8.1.2 Respiration Testing

*In situ* respiration testing was performed at the MOGAS site to determine microbial oxygen utilization rates and potential biodegradation rates. Testing was performed by injecting air (oxygen) into SV-02, SV-03, SV-05, and SV-06 for a 20-hour period. Oxygen, TVH, and carbon dioxide concentrations in soil vapor at these points were measured for a period of approximately 24 hours following air injection. The measured oxygen losses were then used to calculate biological oxygen utilization rates.

Oxygen loss occurred at moderate to high rates, ranging from 0.0027 percent per minute (0.162 percent per hour) at SV-05 to 0.030 percent per minute (1.8 percent per

hour) at SV-03. At SV-03, the oxygen content of the soil vapor dropped from 21.0 percent to 1.0 percent in 24 hours. Oxygen utilization rates are depicted graphically in Appendix H.

Based on these oxygen utilization rates, an estimated 1,000 to 5,000 mg of fuel per kg of soil can be degraded each year at this site. The conservative estimates are based on a ratio of 3.5 mg of oxygen consumed for every 1 mg of fuel biodegraded (ES, 1993). Actual degradation rates may exceed these estimates.

## **8.2 SVE PILOT TESTING**

SVE was evaluated as a potential remedial technology for the treatment of volatile hydrocarbon vapors in the unsaturated zone at the MOGAS site. Extracting vapor from contaminated soils serves two purposes: volatilizing BTEX compounds from unsaturated soils, and supplying oxygen to soils to enhance biodegradation of less volatile compounds.

The depth and radius of oxygen influence resulting from vapor extraction during pilot testing is one of the primary design parameters for full-scale SVE systems. Optimization of full-scale, multiple-well systems requires pilot testing to determine the radius of influence that can be treated at a given flow rate and vacuum. The following subsections summarize the SVE test procedures and results, and assess the applicability of this technology for source reduction at the MOGAS site.

### **8.2.1 SVE Well Installation**

Two 4-inch-diameter PVC vent wells (VENT-01 and VENT-02) were installed at the MOGAS site in August 1996 (Figure 2.2). Each of these wells is screened from 3.5 to 11 feet bgs, and the screen slot size is 0.020 inch. As indicated by the site stratigraphy shown on Figures 3.2 and 3.3, the vent wells are screened across the water table in sand and silty sand. As described in Section 5.4, the majority of residual soil contamination at the MOGAS site was encountered within the 3-foot intervals above and below the water table (approximately 7 to 13 feet bgs). Borehole logs and well construction diagrams are included in Appendix C.

### **8.2.2 SVE Test Procedures**

An SVE pilot test was performed at the MOGAS site during the period from October 20, 1995 to January 30, 1996, to determine the feasibility of reducing fuel vapor contamination within shallow source area soils. Initial soil gas oxygen and carbon dioxide concentrations were measured at monitoring points SV-01 through SV-08 prior to extracting soil vapor from the vent wells (Table 8.1). Soil vapor was extracted from VENT-01 from October 20 to November 7, 1995 (19 days), and from VENT-02 from November 7, 1995 to January 30, 1996 (84 days). Vapors were extracted and treated with a VR Systems' Model V2C internal combustion engine (ICE). This treatment system uses a modified automobile engine to extract and combust volatile hydrocarbon vapors. Manufacturer's information on the ICE is presented in Appendix H. Extraction rates and pressures were varied throughout the

**TABLE 8.1**  
**OXYGEN UTILIZATION RATES DURING INITIAL BIOVENTING PILOT TESTING**  
**MOGAS CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Sampling Location	O2 Loss <sup>a/</sup> (%)	Test Duration <sup>b/</sup> (min)	O2 Utilization Rate <sup>c/</sup> (%/min)
SV-02	20.5	1445	0.022
SV-03	20.0	1440	0.030
SV-05	3.8	1435	0.0027
SV-06	9.3	1430	0.0066

<sup>a/</sup> Actual measured oxygen loss.

<sup>b/</sup> Elapsed time from beginning of test to time when minimum oxygen concentration was measured.

<sup>c/</sup> Values based on linear best-fit oxygen decay curve.

operation period to minimize mounding of shallow groundwater at the vent wells and to maximize ICE operating efficiency. Air extraction rates varied from 7 to 22 scfm with an average rate of approximately 15 scfm and an average extraction vacuum of approximately 36 inches of water (Table 8.1). Throughout system operation, soil gas VOC concentrations, extraction vacuum, and flow rate were periodically measured and recorded for the ICE influent and effluent air streams via automated, computer-monitored instrumentation and manually at various monitoring points (Table 8.1).

### **8.2.3 SVE Test Results**

#### **8.2.3.1 Radius of Influence**

Changes in soil gas vapor concentrations and vacuum were used to determine the effective radius of influence of the extraction wells. The greatest decrease in TVH concentration was measured at SV-07. Over the course of the 103-day SVE pilot test, TVH concentrations at SV-07 decreased from 64,000 ppmv to 1,000 ppmv. The maximum oxygen increase of 0.0 to 20.8 percent was measured at SV-08, located 30 feet north of extraction well VENT-02. The greatest vacuum, 2.5 inches of water, was also measured at SV-08 (Table 8.2).

#### **8.2.3.2 Potential Air Emissions**

The long-term potential for air emissions into the atmosphere from full-scale SVE operations at this site is low. Emissions would be minimal because of the proven efficiency of VR Systems' ICE treatment technology (typically greater than 99-percent destruction of VOCs). Air sampling conducted during system startup verified that the system was operating with a 99-percent destruction efficiency. ICE effluent vapor samples collected throughout the startup and operation of the SVE test indicate that emissions from the ICE were at least two orders of magnitude below SCDHEC (1995) regulatory limits for benzene.

## **8.3 ADDITIONAL PILOT TEST ACTIVITIES**

Additional remedial technologies are currently being investigated as potential source reduction technologies for the MOGAS site. Specifically, biosparging is under consideration for treatment of shallow dissolved groundwater contamination and residual LNAPL contamination in the smear zone. Additional pilot-scale testing may be performed to evaluate the combined effects of biosparging and SVE prior to full-scale remedial system design. Two sparging wells (AS-01 and AS-02, Figure 2.2) were installed downgradient from the two UST locations in 1995.

A biosparging pilot test would consist of air injection well(s) and several groundwater and vapor monitoring points. Soil gas concentrations and DO would be monitored at the points and wells over the course of the test to assess the ability of the system to uniformly introduce air into the groundwater, and to determine an effective radius of influence for the pilot-scale system. As sparge air enters the capillary fringe and vadose zone, the air (oxygen) would promote bioventing of remaining soil contamination.

**TABLE 8.2**  
**IMPACT OF SVE PILOT TEST ON SOIL GAS CHEMISTRY**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

VAPOR MONITORING POINT	DISTANCE FROM VENT-02 (feet)	INITIAL VALUES (10/5/95)			Day 111 of Testing (1/24/96)		
		TVH (ppmv) <sup>a/</sup>	Oxygen (%)	Carbon Dioxide (%)	TVH (ppmv)	Oxygen (%)	Carbon Dioxide (%)
SV-05	35	13,000 <sup>b/</sup>	0	> 25	10,000 <sup>a/</sup>	12	4
SV-06	20	13,000 <sup>b/</sup>	0	> 25	3,100	18	1
SV-07	15	13,000 <sup>b/</sup>	0	> 25	1,000	20	1
SV-08	30	6,000	0	23	38	21	1

<sup>a/</sup> TVH = total volatile hydrocarbons; ppmv = parts per million, volume per volume.

<sup>b/</sup> TVH concentrations above calibration limit of field equipment.

## SECTION 9

### DEVELOPMENT OF REMEDIAL ALTERNATIVES

As described in Section 4, although no fuel hydrocarbon compounds were detected in soil above the health-protective Tier 1 RBSLs, several compounds were detected at average concentrations above their Tier 1 soil leaching RBSLs. However, as a result of the Tier 2 evaluation described in Section 7, none of the average concentrations exceeded Tier 2 soil leaching SSTLs. This means that soil COPCs will continue to leach from source area soils, but not at sufficient concentrations to result in leachate at concentrations above the Tier 2 groundwater SSTLs. No volatile chemicals were measured in soil gas at concentrations expected either to cause exceedances of the 1989 OSHA PELs or to result in indoor concentrations above the Tier 1 air RBSLs (Section 6.6.1). Although elevated concentrations of TVH (i.e., above the MOGAS LEL of 1.4 percent by volume) were measured in soil gas in 1995, SVE pilot testing conducted in 1995 and 1996 has reduced these concentrations. As documented in Section 8, the average TVH concentration measured at soil gas sampling locations in January 1996, after 111 days of SVE operations, was about 3,500 ppmv, which is about one-half the MOGAS LEL. Consequently, it is not necessary to implement additional engineered soil remediation to protect human receptors and underlying groundwater quality, given the types of exposure likely to occur at this site. However, several fuel hydrocarbon compounds were detected in both groundwater and surface water at concentrations above matrix-specific Tier 2 SSTLs (Section 7). The Bioplume II model results presented in Section 6 of this CAP indicate that residual concentrations of groundwater and surface water COPCs above Tier 2 SSTLs are expected to persist in onsite media for many decades unless some type of active groundwater remediation is implemented at the site.

Therefore, preliminary screening of various remedial approaches and technologies that may be appropriate to expedite attainment of Tier 2 groundwater and surface water SSTLs was conducted (see Appendix I). In addition to land and groundwater use controls, natural chemical attenuation, public education, and long-term groundwater and surface water monitoring, three candidate source reduction/contaminant containment alternatives were retained from this screening step as technically feasible and cost-effective approaches to expedite attainment of the target risk-based cleanup objectives for this site (i.e., the Tier 2 SSTLs) in a reasonable time frame. The three retained source reduction/contaminant containment alternatives are:

- Air sparging with resulting concurrent, incidental bioventing;

- Enhancement of aerobic biodegradation using an oxygen-release compound installed in the saturated zone combined with air sparging and bioventing; and
- Groundwater extraction and aboveground treatment combined with SVE.

The benefits (and potential disadvantages) of using these active forms of engineered remediation to supplement exposure controls and natural chemical attenuation to pursue compliance with Tier 2 SSTLs (and eventually, attainment of Tier 1 RBSLs) are described in this section. Each alternative is more fully explained in terms of its effectiveness, technical and administrative implementability, and cost. Following this evaluation, an implementation plan for the proposed corrective action is summarized in Section 10.

## 9.1 SUMMARY OF CANDIDATE REMEDIAL ALTERNATIVES

Based on the initial remedial screening process, which is summarized in Appendix I, several remedial approaches and technologies were retained for the development of remedial alternatives. These technologies were selected to provide a range of passive to more active response actions, all of which can attain Tier 2 SSTLs in all impacted media criteria in slightly different time frames and at different costs. Tier 1 RBSLs also will eventually be achieved by the implementation of any of these remedial alternatives, although compliance with Tier 1 RBSLs is not a primary objective of the corrective action. The following remedial approaches and technologies were retained as potential elements of the preferred corrective action:

- Limited administrative land use controls;
- Groundwater use controls;
- Natural chemical attenuation of soil, groundwater, and surface water/sediment COPCs;
- Long-term groundwater and surface water monitoring;
- Public education;
- Air sparging for treatment of saturated soil and groundwater contamination in the source area (with anticipated incidental bioventing of capillary fringe and vadose zone soils);
- Air sparging for treatment of groundwater contamination near the upgradient bank of the southern drainage ditch to prevent unacceptable COPC discharges into surface water and to expedite groundwater remediation;
- Creation of an oxygen barrier near the upgradient bank of the southern drainage ditch using an oxygen-release compound to enhance natural biodegradation of BTEX compounds, prevent unacceptable COPC discharges into surface water, and expedite groundwater remediation;

- Groundwater extraction to contain the dissolved contaminant plume, lower the water table to allow remediation of contaminated soil zones below the average water table using SVE, and remove dissolved contaminants;
- Aboveground treatment of extracted groundwater using granular activated carbon (GAC) and disposal of treated groundwater in the sanitary sewer; and
- SVE of vadose zone soils with aboveground treatment of extracted vapors using an internal combustion engine (ICE).

The engineered remedial approaches and technologies listed above can be grouped into three categories: ✓

1. Exposure controls to minimize the potential for human receptors to come into contact with site-related contamination (including land and groundwater use controls and public education);
2. Source reduction technologies to accelerate removal of COPCs from the shallow groundwater and saturated soils in the vicinity of the former UST locations and between these locations and the drainage ditch by supplementing natural chemical attenuation processes (including air sparging/bioventing or SVE in the source area and groundwater extraction); and
3. Plume control measures to prevent unacceptable groundwater discharges into surface water (including creation of an air sparging curtain or installation of an oxygen-release barrier near the drainage ditch and groundwater extraction).

It should be noted that incidental bioventing of capillary fringe and vadose zone soils as a result of air sparging is anticipated, especially when seasonal drops in the groundwater table elevation expose capillary fringe soils.

#### 9.1.1 Need for Engineered Corrective Action

W/A  
only

Although Section 6 presents evidence that groundwater COPCs are being reduced in mass, concentration, and toxicity by natural chemical attenuation processes, the Bioplume II model developed for the MOGAS site as part of the Tier 2 chemical fate assessment suggests that concentrations of dissolved benzene, an indicator groundwater COPC, will not be reduced below its Tier 2 groundwater SSTL of 240 µg/L at every point at the site until the year 2085 unless some type of engineered remediation is undertaken (Figure 6.9). Additionally, this model predicts that benzene could continue to discharge into the drainage ditch at concentrations above the Tier 2 surface water SSTL of about 100 µg/L for approximately 110 years. These model results likely overestimate the mass of benzene that will be detected in surface water over time, because the effects of natural chemical attenuation processes in surface water were not factored into the model. Nonetheless, benzene was detected in surface water in 1995 at 580 µg/L, which is more than five times the health-based Tier 1 surface water SSTL of about 100 µg/L.

with source reduction

Therefore, attainment of Tier 2 SSTLs in both groundwater and surface water could not be demonstrated for at least 90 years if only natural chemical attenuation with long-term monitoring were to be implemented at this site. The Air Force recognizes that this is not a reasonable corrective action time frame. Consequently, some form of engineered remediation is warranted to supplement the benefits of natural chemical attenuation processes and land use controls. Because fuel hydrocarbon compounds have been detected in groundwater and surface water at concentrations above Tier 2 SSTLs, the Air Force has developed three remedial alternatives to more rapidly achieve the desired contaminant reductions.

*Source  
Area  
15/1/7*

**9.1.2 Alternative 1 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, and Air Sparging in the Source Area and Adjacent to the Drainage Ditch**

Goal of Alternative 1 - Attainment of Tier 2 industrial SSTLs in groundwater approximately 4 years after initiation of air sparging.

Natural chemical attenuation processes have been removing, and should continue to remove, contaminant mass and limit contaminant migration (Section 6). Unfortunately, these processes alone are insufficient to reduce COPCs to matrix-specific Tier 2 SSTLs within a reasonable time frame. Land and groundwater use restrictions also are considered necessary components of any corrective action at this site to ensure that the exposure assumptions used to develop the Tier 2 SSTLs are representative of site exposure conditions. Land use plans indicate that site access will be open to business activities. The only restrictions will be that excavations below five feet in the contaminated zone will be forbidden, and any excavation/activities in the contaminated zone must not disturb the remediation and monitoring systems. In addition, installation of potable water wells in the surficial aquifer will be forbidden. Maintaining the light industrial land use at this site, and minimizing unrestricted access to use of surface water in the drainage ditch, are consistent with the planned near-term use of this site. Limitations on groundwater use (i.e., groundwater cannot be used as a potable drinking water source until Tier 1 RBSLs have been uniformly achieved throughout the site) will not impose additional restrictions on the current or planned new-term future use in this uninhabited industrial area. Groundwater and surface water monitoring also should be implemented to track the progress of both natural and engineered remediation and to verify that no unacceptable receptor exposures could occur while remediation is in progress.

To eliminate potential unacceptable exposure to benzene, ethylbenzene, and naphthalene in groundwater and to benzene in surface water, Alternative 1 includes a low-cost source reduction/containment technology (air sparging). Because natural chemical attenuation processes will not be sufficient to reduce groundwater COPCs to below Tier 2 SSTLs in a reasonable time frame, implementation of air sparging in the source area would expedite reductions in contaminant concentrations in vadose zone, capillary fringe, and saturated soils in the source area. The air sparging network recommended in Alternative 1 should increase the DO concentration in saturated soils and groundwater to about 1 to 2 mg/L within the source area and immediately adjacent to the northern bank of the southern drainage ditch. The configuration of this air

sparging network is presented on Figure 9.1. The expected performance of this remedial technology is reviewed in Section 9.2. In summary, this system is expected to achieve Tier 2 SSTLs for groundwater and surface water following 4 years of continuous operation (i.e., from the year 1997 through the year 2001). Surface water sparging during this time frame also could be implemented as a contingency action if monitoring results indicate that concentrations of benzene persist in drainage ditch surface water.

Following completion of engineered remediation, COPC concentrations in groundwater will continue to diminish due to the effects of natural attenuation. The Bioplume II model predicts that dissolved benzene concentrations in groundwater will decrease to or below the unrestricted-use RBSL of 5 µg/L by approximately year 2006, assuming that the contamination source is removed within a 4-year time frame as described above.

Incidental bioventing of vadose zone soils is anticipated as oxygen injected into the subsurface diffuses through the groundwater and capillary fringe soils. An oxygen respiration test was performed by Parsons ES at the MOGAS site in 1995. The results of this test are presented in Section 8.1.2. The test results indicate that even incidental bioventing should effectively remove residual fuel hydrocarbons from unsaturated soils and possibly capillary fringe soils at the MOGAS site. The reduction of contamination in the source area via incidental bioventing will serve to reduce the total mass of contamination in groundwater (i.e., expedite attainment of Tier 2 SSTLs and eventually Tier 1 RBSLs), as well as to reduce the total mass of contamination that can migrate to and discharge into the downgradient drainage ditch. No adverse impact on the ambient atmosphere as a result of incidental bioventing/air sparging is expected, because SVE pilot-scale operations have already considerably reduced soil gas VOC concentrations. Soil gas flux testing would be performed during air sparging system startup to assure that contaminant vapors are not migrating from the subsurface at hazardous concentrations.

This alternative would include quarterly monitoring of groundwater and surface water for 1 year, followed by 5 years of semiannual sampling to verify that the specified combination of natural attenuation processes and engineered remediation is sufficient to reduce site concentrations to below Tier 2 industrial SSTLs within the specified time frame. The progress of natural attenuation will be monitored using the existing network of monitoring wells. Additional details on the well locations and the frequency and types of groundwater analysis recommended to confirm the effectiveness of ongoing natural processes and to verify the completion of a cleanup appropriate for an industrial site are presented in the long-term monitoring plan included in Section 10.

#### **9.1.3 Alternative 2 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, Air Sparging in the Source Area, and Installation of an Oxygen-Release Compound Adjacent to the Drainage Ditch**

*SVR in source area*

Goal of Alternative 2 - Attainment of Tier 2 industrial SSTLs in groundwater approximately 4 years after installation of the plume containment barrier and initiation

of air sparging in the source area.

This alternative is similar to Alternative 1, except that the air sparging curtain adjacent to the northern bank of the drainage ditch would be replaced by plume barrier formed by the installation of an oxygen-release compound in the saturated zone. Dissolved BTEX compounds migrating through the oxygen-release compound barrier would be aerobically biodegraded. All other aspects of this alternative are identical to Alternative 1. As with Alternative 1, a 4-year remediation time frame is assumed because the limiting factor is still the rate at which residual soil contamination, which is the source of the dissolved contamination in groundwater, is remediated by the source area air sparging and accompanying incidental bioventing.

Use of the oxygen-release compound ORC<sup>®</sup>, manufactured by REGENESIS Bioremediation Products, is assumed. ORC<sup>®</sup> is a proprietary formulation of magnesium peroxide (MgO<sub>2</sub>), which is the active agent. The product contains both magnesium oxide (magnesia, MgO) and magnesium peroxide, as well as a few percent of food-grade potassium phosphate. The ORC<sup>®</sup> would be introduced in the saturated zone by hanging 1-foot-long filter socks containing ORC<sup>®</sup> in closely-spaced (5-foot centers), 4-inch-ID, PVC wells drilled to an estimated depth of 14 feet bgs. A total of seven ORC<sup>®</sup> filter socks would be stacked in each well, end to end, to form a 7-foot high oxygen barrier. The average effective lifetime of the ORC<sup>®</sup> filter socks is estimated to be 6 months; therefore, a new set of filter socks would be installed semiannually, and the spent socks would be containerized in 55-gallon drums and disposed of at an approved disposal facility. However, the actual effective sock life will vary depending on the average groundwater velocity and the actual dissolved BTEX concentrations contacting the ORC<sup>®</sup> barrier over time.

A potential advantage of using ORC<sup>®</sup> compared to the air sparging curtain is that higher DO concentrations can be achieved by the chemical release of pure oxygen into the groundwater (40 mg/L limit) as opposed to the release of oxygenated air from an air sparging system (8 mg/L limit).

#### **9.1.4 Alternative 3 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, SVE in the Source Area, and Limited Groundwater Extraction with *Ex Situ* Treatment**

Goal of Alternative 3 - Attainment of Tier 2 industrial SSTLs in groundwater approximately 3 years after initiation of SVE and groundwater extraction.

This alternative combines active groundwater extraction/treatment and SVE activities in the source area with natural attenuation. Three 4-inch-ID extraction wells would be installed in the benzene plume at the approximate locations shown on Figure 9.2. Each well would be screened across the uppermost 10 feet of the saturated zone. The influence of the extraction system was simulated using a modified version of the Bioplume II model MOGAS\_2 (see Section 6.6.3). This model was modified by removing the simulated air sparging curtain near the drainage ditch, and adding the three groundwater extraction wells depicted on Figure 9.2, each pumping 2 gallons per minute (gpm). An abbreviated (3-year) source life was retained in the model to

stimulate the effects of an SVE system. Groundwater extraction was assumed to begin at the same time as SVE. Model results indicate that the simulated groundwater extraction system would significantly reduce or eliminate discharge of dissolved contaminants to the drainage ditch. In addition, the water table drawdown throughout most of the area surrounded by the 1,000- $\mu\text{g/kg}$  soil BTEX isopleth (Figure 5.3) is projected to be at least 2 feet in order to dewater the portion of the contaminant smear zone that is below the average water table and allow the SVE system to more completely treat this interval. The model predicts that the net effect of the combined groundwater extraction/SVE system will be attainment of Tier 2 SSTLs after 3 years of continuous operation.

The model results indicate that this pumping rate and drawdown would ensure that the most contaminated groundwater at the site would be removed and treated, and that discharge of COCs to the ditch would be substantially reduced or eliminated. The influx of electron acceptor enriched groundwater from outside the plume area also will enhance natural biodegradation throughout the most contaminated portion of the plume. The removal of residual contaminants sorbed to saturated soils will be enhanced if the most contaminated soil interval is dewatered and exposed to allow more rapid volatilization via SVE.

Prior to final system design and installation, a 24-hour pumping test in one extraction well would be performed to provide the necessary site-scale information to allow the design of a suitable pumping strategy to contain and extract the plume of contaminated water and obtain the desired drawdown in the area influenced by the SVE system. The test results will be used to confirm design parameters such as pumping rate and capture zone radius.

*Ex situ* groundwater treatment would be accomplished using a fabric prefilter followed by GAC canisters connected in series to prevent contaminant breakthrough. Contaminant concentrations would be expected to decrease rapidly over time during the operation of the pump-and-treat system, as would carbon replacement requirements. The canisters and prefilter would be placed in a temporary, low-profile building that would be located at or adjacent to the MOGAS site. Following treatment, groundwater would be discharged into the sanitary sewer at Building 507. A discharge permit would be required, as would monthly influent and effluent monitoring.

The SVE system would be powered by a modified ICE. The ICE would burn the extracted hydrocarbon vapors as fuel, relying on a supplemental fuel source (e.g., propane) as necessary to maintain operation. It is assumed that additional offgas treatment would not be required; however, periodic influent and effluent monitoring (vapor sampling) would be necessary.

Land and groundwater use controls similar to Alternative 1 are recommended until groundwater COCs are reduced below Tier 2 industrial cleanup criteria. During groundwater extraction and SVE, and for at least 2 years following shutdown of the remedial systems, long-term groundwater monitoring would continue in accordance with the long-term monitoring plan.

## **9.2 DETAILED EVALUATION OF REMEDIAL ALTERNATIVES**

### **9.2.1 Summary of Evaluation Criteria**

The evaluation criteria used to assess the potential benefits and disadvantages of the three remedial alternatives described above were adapted from those recommended by USEPA (1988 and 1993) for evaluating remedial actions for Superfund sites [Office of Solid Waste and Emergency Response (OSWER) Directive 9355.3-01]. These criteria include (1) anticipated effectiveness in meeting target cleanup criteria (i.e., Tier 2 SSTLs), (2) technical and administrative implementability, and (3) relative cost. An initial screening of potential remedial approaches and technologies was conducted using these three broad evaluation criteria (Appendix I). The following sections briefly describe the scope and purpose of each criterion.

#### **9.2.1.1 Effectiveness**

The remedial alternatives were evaluated to determine how effectively they can attain the desired degree of cleanup. The alternatives were each designed to remediate groundwater to health-protective Tier 2 groundwater SSTLs (and eventually to Tier 1 RBSLs) and to prevent additional surface water discharges of benzene above its health-protective Tier 2 surface water SSTL. The ability to implement an engineered source reduction/contaminant containment system that minimizes potentially adverse impacts on surrounding facilities and operations and other environmental resources is considered. Time to implementation and time until at least Tier 2 SSTLs are uniformly achieved are described. Potentially adverse impacts that could be realized during implementation, the cost of necessary mitigation measures, and the potential for residual risks remaining following corrective action is considered qualitatively. Long-term reliability for providing continued protection, including an assessment of potential for failure of the corrective action and the potential threats resulting from such a failure, also is evaluated.

#### **9.2.1.2 Implementability**

The technical feasibility, applicability, and reliability of potential remedial approaches and technologies were initially used as broad criteria to narrow the list of potentially applicable remedial approaches for the site (Appendix I). The engineering implementation, reliability, constructability, and technical/logistical feasibility of the remedial alternatives resulting from the preliminary screening presented in Appendix I are described. Potential effects due to unanticipated site conditions or significant changes in site conditions are presented. The ability to monitor system performance and public perception are discussed. Any prohibition of onsite activities that would be required to ensure successful implementation is described.

#### **9.2.1.3 Cost**

The relative cost of various remedial approaches and technologies was used as an initial screening tool (Appendix I). More detailed cost estimates were prepared and presented in this section for the three retained remedial alternatives. The costs include

operation and maintenance costs, over the time required for implementation. Present-worth cost estimates were prepared in accordance with OSWER Directive 9355.3-01 and related guidance (USEPA, 1993).

## **9.2.2 Alternative 1 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, and Air Sparging in the Source Area and Adjacent to the Drainage Ditch**

### **9.2.2.1 Effectiveness**

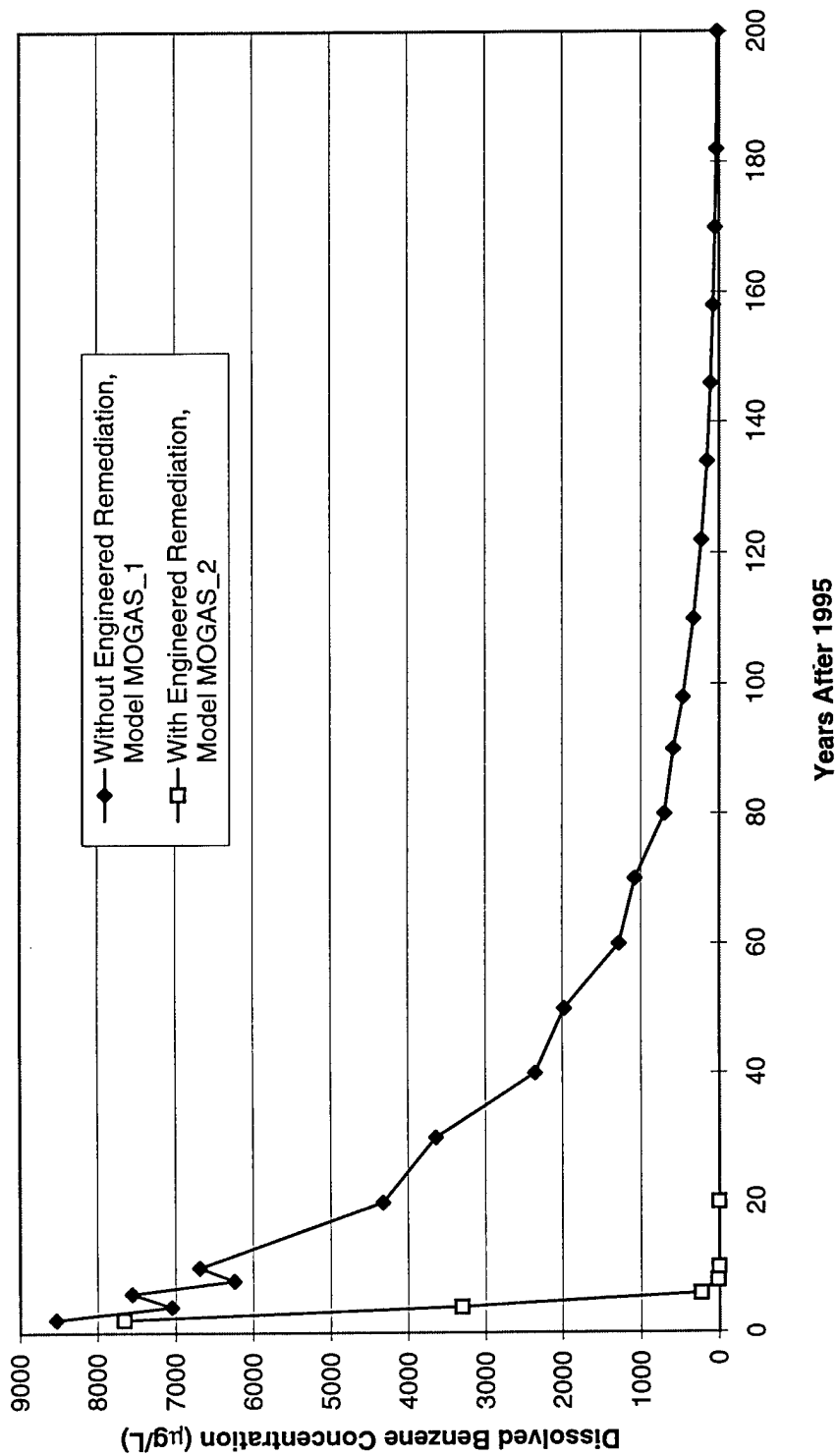
The Tier 2 evaluation, presented in Section 7, indicates that residual site concentrations of benzene, ethylbenzene, and naphthalene in groundwater and benzene in surface water exceed health-protective Tier 2 matrix-specific SSTLs. Although contaminant concentrations are expected to decrease slowly over time as a result of naturally occurring destructive and nondestructive attenuation processes, Tier 2 groundwater SSTLs will not be uniformly achieved until the year 2085. Additionally, the Bioplume II model, which does not account for the effects of chemical attenuation processes operating in surface water, predicts that benzene could continue to discharge into the drainage ditch surface water at concentrations above the health-protective Tier 2 surface water SSTL until the year 2105.

Consequently, the possibility of implementing air sparging at this site to expedite attainment of Tier 2 groundwater and surface water SSTLs was explored. To evaluate the potential effectiveness of such an approach, the Bioplume II model developed for the MOGAS site also was used to simulate the effects of air sparging groundwater and saturated soils (with incidental bioventing) in the source area and near the drainage ditch. Details on the modeling approach are presented in Appendix F. In summary, the anticipated impact of implementing the proposed air sparging network (Figure 9.1) was incorporated into the Bioplume II model by:

- Injecting oxygen into the model grid cells within an assumed radius of influence of 7 feet from each sparging well location such that the DO concentrations in the groundwater were increased to approximately 1.5 mg/L, and
- Incrementally reducing the source strength of benzene in the model over a 3-year period to account for the combined effects of air sparging and incidental bioventing on residual soil contamination.

The degree of oxygen enhancement and the source benzene reductions are believed to be reasonably representative of how site conditions would change if an air sparging system were installed at this site in the proposed configuration.

Figure 9.3 presents the projected impact of implementing the proposed air sparging system at the MOGAS site on dissolved benzene concentrations over time. For comparison purposes, Figure 9.4 presents the projected concentrations of dissolved benzene at the site if no form of engineered remediation is undertaken at the site. The Figure 9.4 predictions are based on the model results presented in Section 6.6.3. Additionally, Figure 9.5 compares the projected impact of air sparging to the impact of



**FIGURE 9.5**

**SIMULATED MAXIMUM BENZENE  
CONCENTRATIONS AT  
DRAINAGE DITCH OVER TIME**

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**  
Denver, Colorado

natural attenuation alone on the concentrations of benzene expected to be discharging into the drainage ditch.

The Bioplume II model results indicate that the maximum dissolved benzene concentration in MOGAS site groundwater would decrease below the Tier 2 groundwater and surface water SSTLs after about 4 years of continuous air sparging operations. It can reasonably be assumed that the effects of air sparging on other dissolved fuel contaminants (e.g., ethylbenzene and naphthalene) would be similar. Consequently, the major benefit derived from implementing air sparging at the MOGAS site would be to reduce the compliance time required to uniformly achieve Tier 2 SSTLs, while minimizing the mass of contamination that could be released into downgradient surface water (i.e., the drainage ditch). If the proposed air sparging system is installed in the spring of 1997, the modeling results indicate that uniform attainment of Tier 2 SSTLs can be expected during the year 2001. Additionally, this model predicts that air sparging is expected to sufficiently reduce contaminant concentrations so that natural chemical attenuation processes can reduce residual contamination to concentrations below Tier 1 groundwater and surface water RBSLs within an additional 5 years (i.e., during the year 2006). After Tier 1 RBSLs are uniformly attained at the site, no restrictions on groundwater use would be required to protect potential receptors from unacceptable exposure. It should be noted that the air sparging simulation only accounts for benzene reduction resulting from aerobic biodegradation. Benzene losses also will occur as a result of volatilization; therefore, the effectiveness of the sparge curtain at reducing discharge of VOCs into the drainage ditch may be greater than predicted using the Bioplume II model.

Some researchers have cast doubt on the long-term effectiveness of air sparging. Problems such as channeling, which consists of preferential migration of injected air along specific (more permeable) flow paths rather than uniform air dispersal in the zone surrounding and overlying the sparging well screen, have been cited. The occurrence of channeling could reduce the integrity of the sparging curtain in some areas, and allow contaminants to migrate past the curtain. Despite its current popularity, some researchers still consider biosparging to be an experimental technology with relatively few documented successes. Use of relatively low injection pressures and air pulsing can potentially reduce the occurrence of channeling.

In addition to exposure controls (i.e., land and groundwater use restrictions), groundwater and surface water monitoring are recommended to measure the effectiveness of the proposed corrective action. The groundwater monitoring network would consist of about 10 permanent monitoring wells and 4 permanent surface water monitoring locations. Quarterly sampling of all monitoring locations is recommended for the first year of corrective action to measure the anticipated significant impact of air sparging on dissolved contaminant mass and to assess the potential for seasonal trends in contaminant distribution patterns. Pending the results of these sampling events, the frequency of monitoring activities for the remaining 3 years may be reduced to twice each year. Once the air sparging system has reduced residual COPC concentrations to below the Tier 2 SSTLs (anticipated after 4 years of operation), or when monitoring data indicate that the system has reached asymptotic contaminant mass removal levels, the air sparging system will be shut down and decommissioned, and verification

monitoring activities will commence. Two years of verification sampling are proposed as part of this corrective action to confirm uniform and stable reductions in COPC concentrations. Specific implementation details can be found in Section 10, the implementation plan for the proposed corrective action.

In the event that the corrective action is not progressing as expected and/or additional releases of elevated concentrations of benzene to drainage ditch surface water are indicated by sampling data, the following contingency actions could be taken:

- Resample all monitoring locations to confirm initial results;
- Evaluate the results of the most recent sampling event to determine if there is a trend indicating that the air sparging system is not achieving uniform decreases in contaminant concentrations (e.g., is channeling suspected?) or if natural chemical attenuation processes have significantly changed (e.g., observing less significant attenuation in surface water?);
- Reevaluate CSM to determine if unacceptable exposure could occur given actual site and downgradient land and groundwater uses; and
- If there is a significant potential for unacceptable exposure and the proposed corrective action is deemed insufficient to reduce that potential, reevaluate more active methods of remediation (e.g., surface water sparging, limited groundwater extraction and treatment).

#### **9.2.2.2 Technical/Administrative Implementability**

Alternative 1 would require the installation of approximately 66 additional air sparging wells (to supplement the two existing air sparging wells installed in 1995), as well as 5 additional air sparging monitoring points (to supplement the 8 existing monitoring points installed in 1995). An estimated total of 19 air sparging wells would be installed along the upgradient bank of the drainage ditch to provide a contaminant treatment "curtain" as well as to enhance source reduction (Figure 9.1). The remaining 47 air sparging wells would be installed along lines perpendicular to the "curtain" and extending into the two primary source areas near the former UST locations. All air sparging wells and monitoring points are proposed to be installed using the Geoprobe® system under the direction of a South-Carolina-certified professional geologist. Two air injection blowers would be installed at the site, and buried air lines would be manifolded to each air injection well. The blower systems would be placed near the sparge wells and electrical service would be obtained from Building 507. Further details on system installation, startup, and operation and maintenance are presented in Section 10.

All equipment required for the air sparging system can be installed at the MOGAS site with a minimal degree of difficulty. Trenching for air line installation in the asphalt-covered area of the site would require asphalt patching. No additional permanent groundwater monitoring wells are required to track the progress of the proposed corrective action or verify uniform attainment of Tier 2 SSTLs.

The general reliability and maintainability of a shallow air sparging system is high. These are simple mechanical systems. Motors are sealed and do not require lubrication. Air filters provide protection for the air pumps. Filters generally require replacement every 90 to 180 days. It is estimated that the air sparging system (with incidental bioventing) would need to be operational for 4 years to achieve the Tier 2 SSTLs and reduce discharge of contaminated groundwater to the drainage ditch. Long-term groundwater and surface water sampling is a standard procedure involving minimal worker exposure to contaminated media.

Administrative implementation of Alternative 1 is much simpler than would be required if only natural chemical attenuation processes were being relied upon to achieve Tier 2 SSTLs. This is due primarily to the time required to administratively track and conclude corrective action at the site. For the projected 6-year duration of Alternative 1, Myrtle Beach AFB personnel should periodically communicate plans regarding the future use of the Base and the MOGAS site to the public and SCDHEC. Site access will reportedly be open for business activities. However, any proposed change in land use to other than an industrial use, or any proposed groundwater pumping within 1,000 feet of the lateral or leading edges of the dissolved contaminant plume, should be carefully evaluated. Any future construction or maintenance activities in this area should be planned to minimize deep excavations (i.e., greater than 5 feet bgs) in locations near the source area and should protect the air sparging system, the blower, the underground piping associated with the system, and the network of long-term monitoring wells. Wells should remain locked and protected against damage, tampering, or vandalism. A 6-year corrective action/compliance period should pose few administrative difficulties. This is an obvious benefit when compared to the administrative (logistical) difficulties that could be associated with a 90- to 110-year compliance period if no form of engineered remediation is undertaken at the site.

The public perception of Alternative 1 is expected to be more positive than if the Air Force proposed to rely on natural chemical attenuation processes alone to achieve Tier 2 SSTLs (and eventually Tier 1 RBSLs). Alternative 1 includes low-cost engineered remediation to supplement natural processes to achieve the desired level of risk reduction in a reasonable time frame. The implementation of air sparging at the site will prevent dissolved contaminants that exceed Tier 2 SSTLs, or Tier 1 RBSLs, from persisting onsite for a lengthy period of time (i.e., 6-year compliance time in comparison to 90- to 110-year compliance time). Additionally, although benzene has been detected in one surface water sample above its Tier 2 SSTL, the potential for unacceptable receptor exposure is believed to be low. Natural chemical attenuation processes appear to be sufficient to limit contaminant concentrations downgradient from the discharge area, and exposure controls are likely minimizing the potential for receptors to come into contact with surface water in the drainage ditch. The air sparging system would provide an additional level of protection for surface water by minimizing, and eventually eliminating, the potential for dissolved contamination in groundwater to migrate to and discharge into the drainage ditch. Consequently, Alternative 1 would provide the desired level of risk reduction within a reasonable time frame.

### 9.2.2.3 Cost

The costs associated with the Alternative 1 for the 6 years of implementation are presented in Table 9.1. Detailed cost calculations are presented in Appendix I. Capital costs include the cost of installation of additional air sparging wells, installation of an air sparging injection blower and associated piping, and pilot testing. Four years of sparging operation, monitoring, and testing have been included as annual costs. Costs also would include 6 years of groundwater and surface water monitoring and site management (provided by the Air Force), which would include public education, continued liaison with SCDHEC, and participation in future land use planning. Sampling and well maintenance costs associated with monitoring after attainment of Tier 2 SSTLs has been verified (i.e., expected during the year 2003) are not included in the cost estimate. Using these assumptions and a present-worth adjustment factor of 7 percent, the present-worth cost of Alternative 1 is \$484,929.

### 9.2.3 Alternative 2 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, Air Sparging in the Source Area, and Installation of an Oxygen Release Compound Adjacent to the Drainage Ditch

#### 9.2.3.1 Effectiveness

The effectiveness of Alternative 2 will be similar to that of Alternative 1 because the sole difference between the two alternatives is the mechanism used to create a plume containment barrier along the northern bank of the drainage ditch. Alternative 1 assumes that a barrier is created by forcibly injecting oxygenated air into the subsurface. As described in Section 9.2.2.1, this can potentially cause air channeling and negatively affect the integrity and effectiveness of the sparge curtain. Alternative 2 assumes that a barrier will be created by diffusion of pure oxygen away from an oxygen releasing compound placed in the subsurface. Although the diffusing oxygen would still tend to preferentially migrate through more permeable zones and bypass less permeable zones, the lack of forced air injection may reduce the occurrence of channeling.

Another potential benefit of using an oxygen-release compound is that DO concentrations can be increased to a greater degree by the addition of pure oxygen compared to the addition of air via a sparging system. For example, a pilot study using ORC® (manufactured by REGENESIS Bioremediation Products) at an abandoned gasoline station in New Mexico demonstrated that oxygen levels as high as 20 mg/L were present in the release wells following installation of ORC® in a line of wells (REGENESIS, 1996). The maximum oxygen increase resulting from an air sparging curtain would be approximately 8 mg/L.

*Program results*

**TABLE 9.1**  
**COST ESTIMATE FOR CORRECTIVE ACTION ALTERNATIVE 1**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

<b>Capital Costs Plus 1st Year of Operation and Maintenance</b>	<b>Capital Costs</b>
Biosparging system pilot test	\$26,558
Installation of biosparging system	\$112,992
Biosparging system operation	\$15,151
Soil Gas Sampling/Respiration Testing	\$20,588
Groundwater/ Surface water sampling at 14 locations (Quarterly for 1 year)	\$57,552
Site Management	\$6,000 <i>\$250K</i>
<b>Present Worth Costs<sup>a</sup></b>	
<b>Site Management and Monitoring Tasks (years 2-6)</b>	
Soil gas samples/ Respiration testing (3 years)	\$54,028
Groundwater/ Surface water sampling at 14 locations Semiannually (5 years)	\$117,987
Site Management (5 years)	\$24,602
Biosparging system operation and maintenance (3 years) <i>3 years</i>	\$39,762
<b>Future Tasks</b>	
Confirmatory soil sampling following biosparging	\$9,709 <i>\$200K</i>
<b>Present Worth of Proposed Corrective Action</b>	<b>\$484,929</b>

<sup>a</sup> Based on an annual adjustment rate of 7 percent (USEPA, 1993).

*Best choice?*

A potential drawback to use of an oxygen-releasing compound is predicting the degree to which elevated oxygen concentrations will diffuse into the area between source wells. The degree of diffusion is highly dependent on the groundwater velocity and contaminant concentrations, and local subsurface heterogeneities (e.g., increases in groundwater velocity) could affect the integrity of the plume containment barrier. Assuming the use of 4-inch-ID wells spaced on 5-foot centers, a groundwater velocity of 0.1 ft/day (Section 3.4.2.4), and a distance of 40 feet from the drainage ditch to the ORC® barrier, the mass of oxygen that ORC® would add to the groundwater is theoretically sufficient to eliminate discharge of dissolved BTEX to the drainage ditch. In practice, REGENESIS occasionally recommends a phased approach, with an initial, relatively liberal well spacing. Additional wells can then be added in a subsequent phase as needed to achieve the desired barrier effectiveness. The costs for Alternative 2 assume that all wells will be installed in a single phase (Section 9.2.3.3).

### 9.2.3.2 Technical/Administrative Implementability

Alternative 2 would require the installation of approximately 60 4-inch-diameter wells to a depth of approximately 14 feet bgs. Forty-seven air sparging wells would be installed along lines perpendicular to the oxygen barrier as shown for Alternative 1 on Figure 9.1. Similar to Alternative 1, an estimated total of 5 oxygen monitoring points also would be installed to supplement the 8 existing monitoring points installed in 1995. All wells and monitoring points would be installed under the direction of a South-Carolina-certified professional geologist. An air injection blower and air lines would be installed as described for Alternative 1 in Section 9.2.2.2.

As described for Alternative 1, the general reliability and maintainability of a shallow air sparging system is high. The ORC® barrier is entirely passive, with no mechanical parts. Therefore, the reliability of this system is high. The ORC® socks are roped together and suspended below the static water level in each well. The only maintenance requirement is periodic replacement of the socks to maintain sufficiently elevated DO concentrations in the groundwater. This replacement may be labor-intensive due to the large number of wells (60), but should not present any significant implementability difficulties. It is estimated that 8 sets of ORC® socks would be required over the projected 4-year operation of the barrier wells.

The administrative implementability of Alternative 2 is projected to be very similar to that described for Alternative 1, given the similarity between the two alternatives and the remedial time frames. The public perception of Alternative 2 is also expected to be similar to that described for Alternative 1 in Section 9.2.2.2.

### 9.2.3.3 Cost

The costs associated with Alternative 2 for the 6 years of implementation are presented in Table 9.2. Detailed cost calculations are presented in Appendix I. Capital costs include the cost of drilling and installation of additional air sparging and ORC® wells and installation of an air sparging injection blower and associated piping. Four years of sparging and oxygen barrier operation, monitoring, and testing have been included as annual costs. Annual costs also would include 6 years of groundwater and

**TABLE 9.2**  
**COST ESTIMATE FOR CORRECTIVE ACTION ALTERNATIVE 2**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

<b>Capital Costs Plus 1st Year of Operation and Maintenance</b>	<b>Capital Costs</b>
Biosparging system pilot test	\$26,558
Installation of biosparging system	\$72,917
Installation of ORC barrier plus 1st year of maintenance	\$141,467
Biosparging System operation and maintenance	\$13,192
Soil gas sampling/respiration testing	\$20,588
Groundwater/ Surface water sampling at 14 locations (Quarterly for 1 year)	\$57,552
Site Management	\$6,000
	<b>\$380,16</b>
	<b>Present Worth Costs<sup>a</sup></b>
<b>Site Management and Monitoring Tasks (years 2-6)</b>	
Soil gas samples/ Respiration testing (3 years)	\$54,028
Semiannual replacement of ORC filter socks (3 years)	<u>\$131,035</u>
Groundwater/ Surface water sampling at 14 locations Semiannually (5 years)	\$117,987
Site Management (5 years)	\$24,601
Biosparging system operation and maintenance (3 years)	\$34,620
	<b>\$300,16</b>
<b>Future Tasks</b>	
Confirmatory soil sampling following biosparging	\$9,709
<b>Present Worth of Proposed Corrective Action</b>	<b>\$710,254</b>

<sup>a</sup> Based on an annual adjustment rate of 7 percent (USEPA, 1993).

surface water monitoring and site management (provided by the Air Force), which would include public education, continued liaison with SCDHEC, and participation in future land use planning. Sampling and well maintenance costs associated with monitoring after attainment of Tier 2 SSTLs has been verified (i.e., expected during the year 2003) are not included in the cost estimate. Using these assumptions and a present-worth adjustment factor of 7 percent, the present-worth cost of proposed corrective action is \$710,254. This is more costly than Alternative 1, primarily due to increased well installation costs, costs related to well development and the disposal of development water, soil cuttings, and spent ORC® socks, and the need for periodic replacement of the ORC® socks.

#### **9.2.4 Alternative 3 - Natural Chemical Attenuation, Long-Term Monitoring, Land and Groundwater Use Controls, SVE in the Source Area, and Limited Groundwater Extraction with *Ex Situ* Treatment**

##### **9.2.4.1 Effectiveness**

A three-well groundwater extraction system would be constructed in the benzene plume at the locations shown on Figure 9.2. Slug testing at the MOGAS site indicates the suitability of the shallow aquifer properties for extracting sufficient volumes of groundwater for dissolved contaminant recovery. As described in Section 9.1.4, model simulations indicate that a pumping rate of approximately 2 gpm per well could be used to capture the dissolved benzene plume, substantially reduce or eliminate discharge of dissolved contaminants to the drainage ditch, and achieve a minimum 2-foot drawdown over most of the area characterized by substantial concentrations of residually-contaminated soils. Groundwater extraction within the plume area will more rapidly remove dissolved COPCs and achieve Tier 2 industrial SSTLs for groundwater at the site. The influx of clean groundwater also will accelerate the partitioning of COPCs from saturated soils and add additional electron acceptors to the aquifer to enhance biodegradation. Bioplume II model results indicate that this pumping should reduce all COPCs to concentrations below industrial cleanup criteria levels in 3 years.

Once extracted, groundwater would be treated using GAC. Carbon adsorption is a proven and cost-effective technology for removing all dissolved COPCs present at the MOGAS site. Due to the relatively short time that should be required to attain generic industrial risk-based criteria, and the anticipated low groundwater extraction rates, more capital-intensive technologies such as air stripping were not considered appropriate for this site. The rapid decline in extracted contaminant concentrations should result in lower carbon costs during the second year of pumping. Treated groundwater would be discharged into the nearby sanitary sewer.

Dewatering of the source area during groundwater extraction will make it possible for the SVE system to volatilize residual VOCs adsorbed to soil particles below the average water table. SVE is a proven technology for the reduction of volatile fuel residuals. Volatilization of these compounds will ensure that when pumping is terminated, the groundwater will not become recontaminated from contact with capillary fringe soils. The SVE pilot test performed in 1995 and 1996 demonstrated that the ICE vapor treatment technology was operating with a 99-percent destruction

efficiency (Section 8.2.3.2). Therefore, additional offgas treatment should not be necessary. Groundwater extraction and SVE were selected as the most aggressive approach for reducing all dissolved COPCs below Tier 2 industrial SSTLs. Alternative 3 should rapidly remove the source and reduce the areal extent of groundwater contamination. The more rapid reduction of soil contaminants using SVE also is an advantage of Alternative 3.

One major drawback to the effectiveness of this alternative is the expected lead time required to design, permit, and construct the much more complex groundwater extraction/carbon treatment system with an integrated SVE system. Once operating, however, this intensive treatment system should attain industrial cleanup criteria for groundwater in approximately 2 years. Unfortunately, the lead time for design, permitting, and construction is expected to be at least 9 months. This reduces the time effectiveness advantage when compared to Alternatives 1 and 2.

Land and groundwater use controls for this alternative would be identical to those described for Alternatives 1 and 2, except that the installation and operation of a groundwater extraction and treatment system and SVE system would require additional site access. The groundwater treatment system would require weekly system checks, and at a minimum, monthly monitoring of groundwater influent and treated effluent groundwater. Periodic sampling of ICE influent and effluent also would be necessary to demonstrate compliance with air emissions regulations. In recognition of the COPC mass reduction that should result from this more intensive source removal, the total long-term groundwater monitoring requirement for Alternative 3 has been estimated at 5 years.

#### **9.2.4.2 Technical and Administrative Implementability**

Alternative 3 would require construction of three, 4-inch groundwater extraction wells, and installation of three, 1/3-horsepower submersible pumps with controls, a prefilter, and the installation of a minimum of two 1,800-pound GAC canisters in series. For this engineering estimate, it is assumed that this treatment system would be installed inside Building 507. The SVE/ICE system for the MOGAS site would consist of two air extraction wells, a VR Systems® Model V3C ICE, subsurface piping, supplemental fuel (propane) tank, and accessories such as gauges and filters. Standard mechanical and electrical construction would be used; special construction techniques should not be necessary.

Submersible pumps and carbon treatment systems generally are highly reliable when they are properly maintained. The most frequent reliability problems occur with pump controls, which must be carefully set to minimize pump cycling. Due to the short, 3-year pumping period, the submersible pump should operate with minimal maintenance. The most significant maintenance requirement for this system will be regular replacement of the prefilter element and monitoring of the GAC effluent to ensure that discharge standards are attained. Due to the anticipated rapid decline in extracted COPC concentrations, replacement of the carbon canisters may be required only two or three times during the life of the project. Three sets of replacements have been estimated for cost purposes. The documentation associated with meeting reinjection

monitoring requirements could add several hours each month to project management. SVE/ICE systems are very reliable and require only minimal maintenance. Air filters provide blower protection and generally require replacement every 90 to 180 days. Weekly system checks are recommended, and operating data such as injection pressure and flow rate will be manually recorded. Periodic influent and effluent vapor samples would be required to demonstrate compliance with air emissions requirements.

Administrative implementation of this alternative will require that the Air Force and affected local governments (e.g., Myrtle Beach and Horry County) continue to communicate regarding the future use of the site and the approved zoning be upheld, with appropriate lease restrictions to prevent potable use of site groundwater. The perimeter fence should be maintained to prevent unauthorized entrance. Future development plans should protect the SVE and pumping and treatment systems and network of long-term monitoring wells. Wells should remain locked and protected against tampering.

The public perception of Alternative 3 is expected to be positive. This alternative is protective of human health and the environment and achieves COC reductions that are compatible with the current and projected future industrial land use. However, any benefits of more rapid risk reduction may not be justified, given the additional costs.

#### 9.2.4.3 Cost

The costs associated with Alternative 3 are presented in Table 9.3. Detailed cost calculations are included in Appendix I. Capital costs include the cost of design and construction of groundwater extraction, groundwater treatment, and SVE/ICE systems. Annual costs will include the 3 years of groundwater extraction and SVE, 5 years of groundwater monitoring and site management (provided by the Air Force), which will include public education and continued liaison with all pertinent government agencies, and participation in future land use planning. Based on these assumptions, the present worth cost of Alternative 3 is \$703,315. Alternative 3 costs are most sensitive to additional years of groundwater treatment system operation and maintenance.

### 9.3 RECOMMENDATION

Alternative 1 (installation of an air sparging system to treat the source area and minimize discharges to the drainage ditch, natural chemical attenuation, long-term monitoring, and land and groundwater use controls) achieves the best combination of risk reduction and cost effectiveness. The proposed corrective action is relatively simple with respect to technical and administrative implementation concerns, and relies on relatively low-cost, *in situ* techniques. The capital costs of the proposed action are justified by the expected dramatic decrease in remediation time resulting from the implementation of source reduction activities. In addition, installation of the air sparging "curtain" will minimize discharge of contaminants to the drainage ditch, thereby interrupting this potentially completed exposure pathway. The increased costs associated with Alternative 2 are not justifiable, given that the remediation time frame is expected to be similar to that of Alternative 1. A shorter remedial time frame is

**TABLE 9.3**  
**COST ESTIMATE FOR CORRECTIVE ACTION ALTERNATIVE 3**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

<b>Capital Costs Plus 1st Year of Operation and Maintenance</b>	<b>Capital Costs</b>
Installation of Pump and Treat System	\$137,273
Installation of SVE System	\$95,392
Pump and Treat and SVE system operation/maintenance	\$78,983
Soil gas sampling/respiration testing	\$20,588
Groundwater/ Surface water sampling at 14 locations	\$57,552
(Quarterly for 1 year)	
Site Management	\$6,000
	<i>\$ 380K</i>
	<b>Present Worth Costs<sup>u</sup></b>
<b>Site Management and Monitoring Tasks (years 2-5)</b>	
Operation/maintenance of SVE/pump and treat system (2 years)	\$142,802
Soil gas sampling/respiration testing (2 years)	\$37,223
Groundwater/ Surface water sampling at 14 locations	
Semiannually (4 years)	\$97,470
Site Management (4 years)	\$20,323
	<i>\$ 320K</i>
<b>Future Tasks</b>	
Confirmatory soil sampling following pump and treat/SVE (year 4)	\$9,709
<b>Present Worth of Proposed Corrective Action</b>	<b>\$703,315</b>

<sup>u</sup> Based on an annual adjustment rate of 7 percent.

## **SECTION 10**

### **PROPOSED CORRECTIVE ACTION IMPLEMENTATION PLAN**

This section provides an implementation plan for the recommended risk-based corrective action for the MOGAS site (i.e., air sparging in source area and immediately upgradient from drainage ditch, natural chemical attenuation, monitoring of groundwater and surface water to verify remedial progress, and land and groundwater use controls). This section presents the scope, schedule, and annual costs for the implementation of the proposed corrective action.

#### **10.1 SCOPE OF REMEDIAL ACTIVITIES**

The proposed remedial corrective action will be implemented over a 6-year period to ensure that fuel hydrocarbon contamination in all media at the MOGAS site is reduced sufficiently to attain, at a minimum, the Tier 2 SSTLs presented in Section 7. Emphasis is placed on uniformly achieving both groundwater and surface water SSTLs, although eventually progress toward and attainment of Tier 1 RBSLs is possible. The following sequence of events is proposed to fully implement this corrective action.

##### **10.1.1 Review and Approval of Corrective Action Plan**

Approval of this draft CAP is within the authority of Myrtle Beach AFB, SCDHEC, and AFCEE personnel. This group of environmental professionals is responsible for review of this draft CAP and eventual implementation of the approved corrective actions. A final draft of this document will be distributed to each of the above organizations for review and comment. Approximately 60 days has been designated in the implementation schedule for CAP review and approval.

Following the 60-day review period, a project presentation will be provided by Parsons ES and AFCEE at a location selected by Air Force and state regulatory personnel. The purpose of this presentation will be to describe the major findings of this risk-based remediation project and to receive feedback and discuss any unresolved issues that may surface during document review. This direct interface between the document preparers and the group charged with CAP implementation is essential for a smooth transition into corrective actions. Following the presentation, any unresolved issues or concerns can be provided in writing to AFCEE and Parsons ES for additional discussion and formal incorporation into the final CAP.

##### **10.1.2 Air Sparging System Design, Installation, and Operation**

Installation of up to 66 new air sparging wells is recommended at the MOGAS site to implement air sparging of shallow groundwater. These new wells will supplement

the two existing air sparging wells installed in 1995. The two vent wells for the SVE system will not be used as part of the air sparging system. Air sparging wells will be installed on approximately 15-foot centers in a configuration similar to that presented in Figure 10.1. One-inch PVC sparging wells and 0.5-inch PVC groundwater monitoring points will be installed by a South Carolina certified professional geologist manually or using the Geoprobe® system. New air sparging wells with 2-foot screens will be manually placed approximately 8 feet below the groundwater table. The air sparging wells will be manifolded via HDPE tubing laid in narrow 1- to 2-foot deep trenches. This approach will make the air sparging system more durable, and should involve less asphalt cutting. The air sparging blowers will be placed near the source area. In addition, up to 5 new multi-level groundwater monitoring points will be installed, and screened at depths of 2, 6, and 10 feet below the groundwater surface. These points will be used to collect groundwater data before the initial startup and to monitor the effectiveness of the air sparging system. Proposed locations for additional air sparging wells, new groundwater monitoring points, and blower are shown in Figure 10.1. A conceptual cross-section of the proposed air sparging system is presented in Figure 10.2.

During the startup of the air sparging system, air injection rates will be optimized to minimize contaminant volatilization and maximize biodegradation potential. After system startup and optimization, periodic monitoring of the system will be required. A basic system check will be completed by Base personnel every other week to assure proper operation. The air injection temperature and pressures will be recorded, and the inlet air filter will be changed as necessary. In addition, Parsons ES will visit the site six times every year to conduct basic monitoring activities. Then, every 6 months during the first 2 years of system operation, *in situ* respiration and radius-of-influence testing will be performed by Parsons ES to assess soil contaminant biodegradation rates and oxygen influence in soils and groundwater at the MOGAS site. A contract extension will be required for the air sparging system operation and maintenance during the third and fourth years of operation. Results of testing activities will be provided to Myrtle Beach AFB, SCDHEC, and AFCEE to update all parties involved on remediation progress.

At the conclusion of approximately 4 years of air sparging operations, compliance soil samples and verification groundwater and surface water samples will be collected to determine the degree of contaminant reduction. If contaminant levels have been reduced to the Tier 2 SSTLs, or if the monitoring data suggest the system has reached its asymptotic contaminant mass removal limit, the air sparging system will be deactivated. Based on the performance of air sparging systems at sites with similar hydrogeology and concentrations of contamination (Brown *et al.*, 1991; Marley *et al.*, 1990), 4 years should be adequate to uniformly achieve Tier 2 SSTLs. Natural chemical attenuation processes will then be sufficient to eventually reduce residual mass to Tier 1 RBSLs within a reasonable time frame (i.e., during the year 2006). Additional details on system operation and maintenance, compliance sampling, and abandonment procedures can be found in Appendix J.

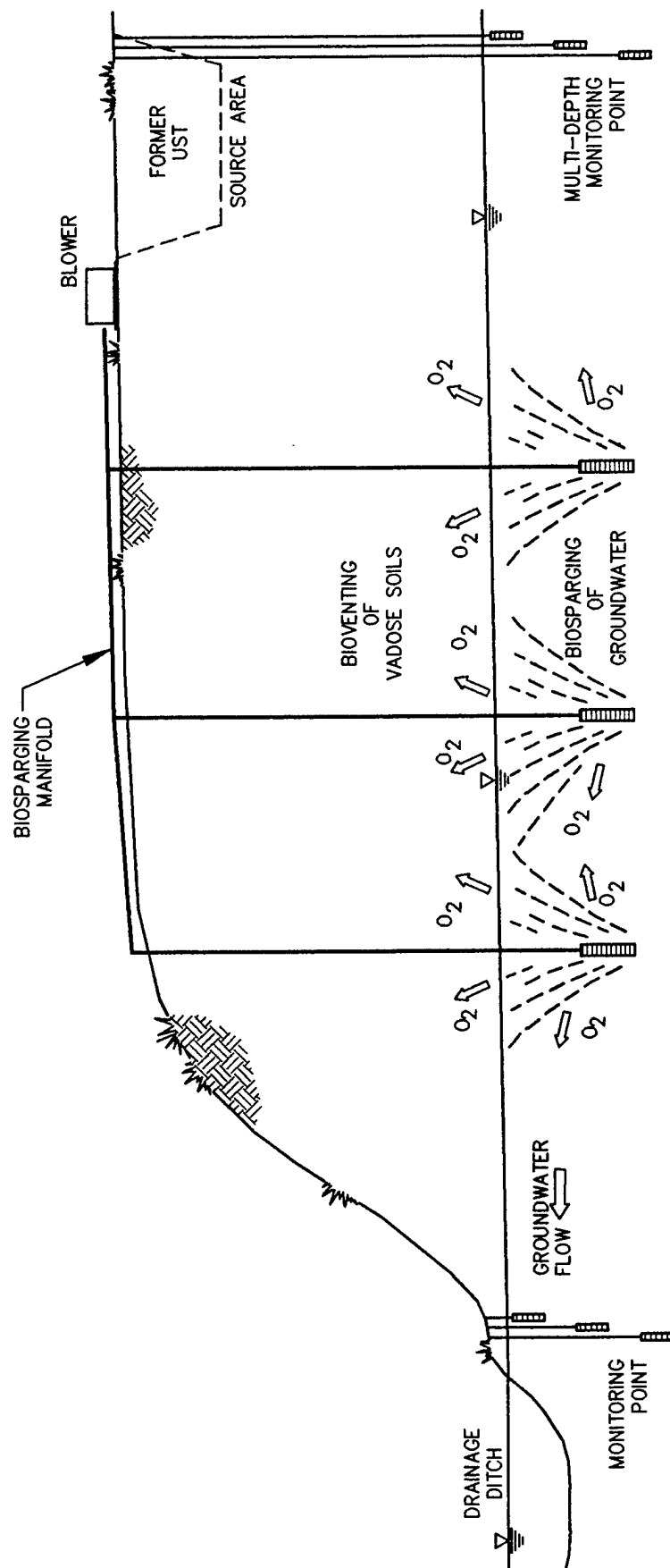


FIGURE 10.2

## CONCEPTUAL BIOSPARGING SYSTEM

MOGAS Site Corrective Action Plan  
Risk-Based Approach to Remediation  
Myrtle Beach AFB, South Carolina

**PARSONS  
ENGINEERING SCIENCE, INC.**

Denver, Colorado

### **10.1.3 Verification of Land and Groundwater Use Controls**

An important element of the recommended corrective action at the MOGAS site is land and groundwater use controls. On the basis of the exposure pathways analysis (Sections 6 and 7), the MOGAS site is and will continue to be acceptable for continued industrial/commercial use provided nonintrusive workers do not come into direct contact with impacted media on a regular basis, intrusive workers do not engage in excavation activities that disrupt the asphalt pavement area near the source area without appropriate personal protective equipment, and access by trespassers/ recreators is minimized.

The target cleanup objectives (i.e., the Tier 2 SSTLs) also are based on the assumption that (near-term) future land use will not require extraction of shallow site groundwater for potable uses. Any future lease or new land uses of this land must stipulate that shallow groundwater will not be extracted within 1,000 feet of dissolved contamination above Tier 1 RBSLs until COPC concentrations have been reduced below applicable concentrations. Excavation in the impacted area also should only be performed by workers who have been briefed on the nature of onsite contamination and trained in proper use of personal protective equipment. These minor restrictions will eliminate potential unprotected exposure of onsite workers to contaminated media at the MOGAS site.

### **10.1.4 Implementation of Groundwater and Surface Water Monitoring**

Section 10.3 of this CAP provides a complete LTMP for the MOGAS site. Long-term groundwater and surface water monitoring is being proposed to verify that engineered source reduction technologies and natural chemical attenuation processes are sufficient to achieve the desired degree of remediation (i.e., protect potential receptors). Careful implementation of the LTMP is a key component of this CAP. The proposed corrective action for this site calls for quarterly sampling of groundwater and surface water for the first year, reverting to semiannual groundwater and surface water sampling for the next 3 years or until attainment of Tier 2 SSTLs. Quarterly sampling is recommended for the first year to track immediate reductions in contaminant mass due to engineered source reduction activities, as well as to develop a data base on the seasonal behavior of contamination. Semiannual (i.e., twice a year) sampling is recommended to coincide with system maintenance schedules, provided no significant seasonal variations in contamination patterns are noted in the first year. Additionally, 2 years of verification sampling, conducted on a semiannual basis, will be performed after air sparging operations cease, to confirm uniform attainment of groundwater and surface water SSTLs. Wells will be purged in accordance with the SAP presented in Appendix J, and then sampled for the parameters listed in Table 10.1. Surface water sampling stations will be permanently staked so that contaminant distribution patterns in surface water can be more accurately documented.

Sampling activities pursuant to this CAP are recommended to begin in mid 1997 upon approval of the final CAP and installation of air sparging system. Results of each groundwater/ surface water sampling event should be provided to Myrtle Beach AFB, SCDHEC, and AFCEE to update all parties involved on remediation progress and to provide new information for pending land use decisions, as necessary.

TABLE 10.1

**GROUNDWATER/SURFACE WATER MONITORING ANALYTICAL PROTOCOL**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site-Specific Water MDL	Practical Quantitation Limit	Field or Fixed-Base Laboratory
Aromatic hydrocarbons (BTEx)	SW8020 (Gas Chromatography/Mass Spectrometry method)	As described in latest version of <i>Test Methods for Evaluating Solid Waste</i> (EPA SW-846)	BTEx compounds (benzene, toluene, ethylbenzene, and total xylenes), naphthalene, and TMBs have been identified as either groundwater COPCs or compounds that can affect biodegradation of groundwater COPCs, benzene has been identified as a surface water COPC	Quarterly for the first year then biannually for the remaining 4 years	Collect water samples in a 40 milliliter volatile organic analysis vial with zero headspace; cool to 4°C; add hydrochloric acid to pH $\leq 2$	See Table 2.1	See Table 2.1	Fixed-base
Polycyclic aromatic hydrocarbons (PAHs)	SW8270 (Gas Chromatography/Mass Spectrometry method)	As described in latest version of <i>Test Methods for Evaluating Solid Waste</i> (EPA SW-846)	PAH compound naphthalene has been identified as a groundwater COPC	Quarterly for the first year then biannually for the remaining 4 years	Collect water samples in a 1-liter glass container, cool to 4°C	See Table 2.1	See Table 2.1	Fixed-base
Dissolved oxygen	Direct-reading meter (YSI Model 50B with YSI 5739 probe)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	Reduced concentrations of dissolved oxygen indicate that microorganisms are facilitating oxygen reduction to biodegrade COPCs	Quarterly for the first year then biannually for the remaining 4 years - Groundwater Only	Measure directly using flow-through cell with probe portals. Probe should be calibrated with zero dissolved oxygen solution	NA	0.5 mg/L	Field
pH	Direct-reading meter (Orion Model 140)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	Aerobic and anaerobic processes are pH-sensitive	Quarterly for the first year then biannually for the remaining 4 years - Groundwater Only	Measure directly using a contained flow-through cell with probe portals. Probe should be calibrated using at least three pH standards	NA	0.00 pH units	Field

**TABLE 10.1 (Continued)**  
**GROUNDWATER/ SURFACE WATER MONITORING ANALYTICAL PROTOCOL**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Site-Specific Water MDL	Practical Quantitation Limit	Field or Fixed-Base Laboratory
Temperature	Direct-reading meter	Field only	Metabolism rates for microorganisms depend on temperature	Quarterly for the first year then biannually for the remaining 4 years - Groundwater Only	Measure directly using a contained flow-through cell with probe portals	NA	1.0 °C	Field
Conductivity	Direct-reading meter (Orion Model 140 with Conductivity Cell 014050)	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	General water quality parameter used as a marker to verify that site samples are obtained from the same ground water system	Quarterly for the first year then biannually for the remaining 4 years - Groundwater Only	Measure directly using a contained flow-through cell with probe portals. Probe is factory calibrated	NA	0.02 µmhos/cm	Field
Alkalinity (as CaCO <sub>3</sub> )	Colorimetric HACH 8221	Field only	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Quarterly for the first year then biannually for the remaining 4 years - Groundwater Only	Collect 100 mL of water in a glass container; filter and use 10 mL aliquot for analysis.	NA	20.0 mg/L	Field

<sup>a/</sup> NA = not applicable

## **10.2 IMPLEMENTATION SCHEDULE**

Figure 10.3 is a proposed schedule for implementation of the CAP at the MOGAS site. The schedule is provided for planning purposes only, and is subject to timely approval of the CAP by Myrtle Beach AFB, SCDHEC, and AFCEE.

## **10.3 LONG-TERM MONITORING PLAN**

The purpose of the LTMP is to confirm the effectiveness of proposed engineered remediation and natural processes at achieving the desired level of risk reduction in a reasonable time frame. As part of this monitoring and compliance plan, contaminant behavior in groundwater and surface water will be monitored to verify that the proposed corrective action is sufficient to remediate groundwater underlying the source area at the MOGAS site and to significantly reduce contamination discharge to the southern drainage ditch. The plan also calls for periodic soil gas sampling to attempt to quantify the VOC removal rates of the air sparging/bioventing system. In the event that data collected under this program indicate that the proposed action is insufficient to eventually achieve groundwater and surface water SSTLs at the MOGAS site, contingency actions will be implemented to augment the effects of the proposed corrective action.

### **10.3.1 Biweekly Monitoring of Air Sparging System Operations**

The proposed full-scale air sparging system is expected to be installed in mid 1997, upon final approval of this CAP. Once system startup and optimization is complete, long-term operation will begin. An operation and maintenance (O&M) manual will be prepared prior to the beginning of extended operation. Parsons ES will prepare the manual as part of system installation and optimization. Contents of the O&M plan for air sparging will include system as-built drawings, vendor equipment specifications, maintenance schedules, and a list of emergency contacts.

System checkups for the air sparging system ideally should be performed every other week. The following activities will typically be performed during a system check:

- Record air injection pressure for the air sparging system;
- Measure the injection blower flow rate and operating temperature;
- Assess the condition of the air inlet filter elements and replace as necessary for systems; and
- Note any unusual operating characteristics (e.g., clogged lines or tripped breakers).

All maintenance activities will be recorded on an O&M checklist and will become part of the site record. Parsons ES will supplement Base monitoring activities six times a year by visiting the site to complete basic O&M requirements. This supplemental system maintenance requirement has been included in the yearly cost estimates presented later in this implementation plan.

## **10.2 IMPLEMENTATION SCHEDULE**

Figure 10.3 is a proposed schedule for implementation of the CAP at the MOGAS site. The schedule is provided for planning purposes only, and is subject to timely approval of the CAP by Myrtle Beach AFB, SCDHEC, and AFCEE.

## **10.3 LONG-TERM MONITORING PLAN**

The purpose of the LTMP is to confirm the effectiveness of proposed engineered remediation and natural processes at achieving the desired level of risk reduction in a reasonable time frame. As part of this monitoring and compliance plan, contaminant behavior in groundwater and surface water will be monitored to verify that the proposed corrective action is sufficient to remediate groundwater underlying the source area at the MOGAS site and to significantly reduce contamination discharge to the southern drainage ditch. The plan also calls for periodic soil gas sampling to attempt to quantify the VOC removal rates of the air sparging/bioventing system. In the event that data collected under this program indicate that the proposed action is insufficient to eventually achieve groundwater and surface water SSTLs at the MOGAS site, contingency actions will be implemented to augment the effects of the proposed corrective action.

### **10.3.1 Biweekly Monitoring of Air Sparging System Operations**

The proposed full-scale air sparging system is expected to be installed in mid 1997, upon final approval of this CAP. Once system startup and optimization is complete, long-term operation will begin. An operation and maintenance (O&M) manual will be prepared prior to the beginning of extended operation. Parsons ES will prepare the manual as part of system installation and optimization. Contents of the O&M plan for air sparging will include system as-built drawings, vendor equipment specifications, maintenance schedules, and a list of emergency contacts.

System checkups for the air sparging system ideally should be performed every other week. The following activities will typically be performed during a system check:

- Record air injection pressure for the air sparging system;
- Measure the injection blower flow rate and operating temperature;
- Assess the condition of the air inlet filter elements and replace as necessary for systems; and
- Note any unusual operating characteristics (e.g., clogged lines or tripped breakers).

All maintenance activities will be recorded on an O&M checklist and will become part of the site record. Parsons ES will supplement Base monitoring activities six times a year by visiting the site to complete basic O&M requirements. This supplemental system maintenance requirement has been included in the yearly cost estimates presented later in this implementation plan.

## 10.4 CONTINGENCY PLAN

Should engineered remediation and natural chemical attenuation processes fail to achieve and maintain groundwater and surface water SSTLs, there should be no significant impact on the immediate land use plans for the site. No nonindustrial land use has been proposed for the MOGAS site for the near-term, however, the site will be open for business activities that do not disrupt the contaminated area and remedial systems. If SSTLs are not achieved at the MOGAS site, restrictive exposure controls may have to be maintained to prevent onsite workers and trespassers/recreators from coming into direct contact with impacted media. Nonetheless, even if the most stringent SSTLs are not met at the MOGAS site, the site may still be suitable for nonintrusive industrial activities.

Once again, failure of the proposed corrective action to immediately achieve risk-based SSTLs should not impact the current or proposed uses of the MOGAS site, as long as suitable exposure controls are maintained. No receptor is in direct contact with groundwater unless intrusive work is conducted at the site, trespasser/recreator contact with contaminated surface water is controlled by limited access to the site, and detectable levels of benzene are expected to migrate no more than approximately 50 feet downstream from SW-01 in the southern drainage ditch (i.e., not west of Third Street) and/or 50 feet downgradient from MW-04 (i.e., not south of Phyliss Drive). Therefore, no receptor (trespassers/recreators) are exposed to contaminated media unless they are present at the MOGAS site. If remediation is not progressing as planned, the following contingency actions are available:

- All wells/ points will be sampled to determine the extent of contamination and to locate the highest COPC concentrations.
- The results of the most recent sampling event will be evaluated to determine if there is a trend indicating that COPC mass reduction is not proceeding as expected.
- The potential for unacceptable exposure to occur with slower rates of natural chemical attenuation and lower rates of engineered remediation effectiveness will be evaluated.
- If significant risk exists, more active methods of remediation, such as pump and treat, will be evaluated.

Groundwater extraction is not anticipated at the site so long as alternate water supplies exist. In the unlikely event that shallow groundwater from the site must be extracted for potable uses, and applicable Tier 1 RBSLs for groundwater have not yet been achieved, the following contingency actions are available:

- The results of the most recent groundwater sampling event will be evaluated to determine if there is a trend indicating that COPCs degradation, with air sparging in the source area, is not proceeding as expected.
- If onsite groundwater is to be used for potable uses before air sparging and natural attenuation processes can achieve Tier 1 RBSLs, more aggressive

groundwater treatment methods such as limited pump and treat will be evaluated and implemented.

### 10.5 Cost of Implementation

A summary of the estimated present-worth cost of implementing the proposed corrective action is provided in Section 9.3.4. Table 10.2 provides a cost estimate, based on estimated expenditures during the next 5 fiscal years, to assist the Air Force in budgeting for implementation of the recommended corrective action. The present worth of implementing the proposed corrective action to uniformly attain and verify SSTLs is \$484,929. It is estimated that it will take about 4 years to attain SSTLs in all affected media. Verification of continuing compliance will require an additional 2 years, for a total projected compliance time frame of 6 years (i.e., 1997 until 2003). In contrast, it is estimated that it would take about 94 to 110 years to attain SSTLs for groundwater and surface water with natural chemical attenuation processes alone.

**TABLE 10.2**  
**PROPOSED CORRECTIVE ACTION IMPLEMENTATION**  
**ESTIMATED COST BY FISCAL YEAR**  
**MOGAS SITE CORRECTIVE ACTION PLAN**  
**RISK-BASED APPROACH TO REMEDIATION**  
**MYRTLE BEACH AFB, SOUTH CAROLINA**

Task	FY97	FY98	FY99	FY00	FY01	FY02	FY03
Air Sparging Pilot Test	\$26,558 <sup>a/</sup>						
Installation of Air Sparging System	\$112,992 <sup>a/</sup>						
Air Sparging Operation and Maintenance	\$7,576 <sup>a/</sup>	\$15,151 <sup>a/</sup>	\$15,151	\$15,151	\$7,576		
Semi-annual Soil Gas Sampling/Respiration Testing	\$10,294 <sup>a/</sup>	\$20,588 <sup>a/</sup>	\$20,588	\$20,588	\$10,294		
Confirmatory Soil Sampling					\$12,726		
Groundwater/ Surface Water Sampling in Accordance with LTMP	\$28,776 <sup>a/</sup>	\$43,164	\$28,776	\$28,776	\$28,776	\$28,776	\$14,388
Site Management	\$3,000	\$6,000	\$6,000	\$6,000	\$6,000	\$6,000	\$3,000
<b>FISCAL YEAR TOTALS</b>	<b>\$189,196</b>	<b>\$84,903</b>	<b>\$70,515</b>	<b>\$70,515</b>	<b>\$65,372</b>	<b>\$34,776</b>	<b>\$17,384</b>

<sup>a/</sup> Currently funded and to be performed by Parsons ES under contract with AFCEE.

## SECTION 11

### REFERENCES

- Abdul, S.A., Gibson, T.L., and Rai, D.N., 1987. Statistical correlations for predicting the partition coefficient for nonpolar organic contaminants between aquifer organic carbon and water, *Hazardous Waste and Hazardous Materials*, vol. 4, no. 3, p. 211-222.
- Acomb, L. J., McKay, D., Currior, P., Berglund, S., Sherhaut, T., Benediktsson, C. 1995. *Neutron Probe Measurements of Air Saturation Near an Air Sparging Well*, presented at In Situ and On-Site Bioreclamation 3rd International Symposium. San Diego, Ca.
- Air Base Redevelopment Commission, General Redevelopment Plan for the Air Base Planning Area, April 1993.
- Altenschmidt, U. and Fuchs, G., 1991. Anaerobic degradation of toluene in denitrifying *Pseudomonas* sp.: Indication for toluene methylhydroxylation and benzoyl-CoA as central aromatic intermediate, *Arch. Microbial.*, vol. 156, p. 152-158.
- Alvarez, P.J.J., and Vogel, T.M., 1991. Substrate interactions of benzene, toluene, and para-xylene during microbial degradation by pure cultures and mixed culture aquifer slurries, *Applied and Environmental Microbiology*, vol. 57, p. 2981-2985.
- American Society for Testing and Materials (ASTM), 1994. *Emergency Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites*, ES 38-94.
- American Society for Testing and Materials (ASTM), 1995. *Standard Guide for Risk-Based Corrective Action at Petroleum Release Sites*, E1739-95.
- Anderson, M. P., and Woessner, W. W.; 1992. *Applied Groundwater Modeling*, Academic Press, Inc., San Diego, California.
- Arthur D. Little, Inc., 1987. *The Installation Restoration Program Toxicology Guide*. vol. 3. p. 64-7 - 64-14. June.
- Atlas, R.M., 1981. Microbial degradation of petroleum hydrocarbons - an environmental perspective: *Microbiological Reviews*, vol. 45, no. 1, p. 180-209.
- Atlas, R.M., 1984. *Petroleum Microbiology*, Macmillan Publishing Company, New York.

- Atlas, R.M., 1988. *Microbiology - Fundamentals and Applications*, Macmillan Publishing Company, New York.
- Baedecker, M.J., Siegel, D.I., Bennett, P.C., Cozzarelli, I.M., 1988. The fate and effects of crude oil in a shallow aquifer: I. The distribution of chemical species and geochemical facies, In: G.E. Mallard, and SE. Ragone, editors, U.S. Geological Survey Toxic Substances Hydrology Program, *Proceedings of the Technical Meeting*, Phoenix, Arizona, September 26-30, 1988: U.S. Geological Survey Water-Resources Investigations Report 88-42320, p. 29-22.
- Baedecker, M.J., and Cozzarelli, I.M., 1991. Geochemical modeling of organic degradation reactions in an Aquifer contaminated with Crude Oil, U.S. Geological Survey Water-Resources Investigations Report 91-4034, Reston, VA., p 627-632.
- Bartha, R., 1986. Biotechnology of petroleum pollutant biodegradation, *Microbial Ecology*, vol. 12, p. 155-172.
- Bauman, B, 1991, Biodegradation research of the American Petroleum Institute, presented at *In Situ Bioreclamation: Application and Investigation for Hydrocarbons and Contaminated Site Remediation*, San Diego, CA., March 19-21, 1991.
- Bear, J., 1972, *Dynamics of Fluids in Porous Media*: Dover Publications, Inc., New York, 764 p.
- Bear, J., 1979, *Hydraulics of Groundwater*: McGraw-Hill, Inc., New York, New York, 569.
- Beller, H.R., Reinhard, M., and Grbic-Galic, D., 1992. Metabolic byproducts of anaerobic toluene degradation by sulfate-reducing enrichment cultures, *Appl. Environ. Microbiol.*, vol. 58, p. 3192-3195.
- Beljin, M., 1989. Solute, A Program of Analytical Models for Solute Transport in Groundwater, International Ground Water Modeling Center, Holcomb Research Institute, Butler University, Indianapolis, IN, 46208.
- Bohon, R.L., and Claussen, W.F., 1951. The solubility of aromatic hydrocarbons in water, *Journal of American Chemical Society*, vol. 73, no. 4, p.1571-1578.
- Borden, R.C., 1991. Simulation of enhanced in situ bioremediation of petroleum hydrocarbons, *In Situ Bioreclamation: Application and Investigation for Hydrocarbons and Contaminated Site Remediation*. Eds., R.E. Hinchee and R. F. Olfenbittel. Butterworth-Heinemann. p. 529-534.
- Borden, R.C., 1994. Natural Bioremediation of Hydrocarbon-Contaminated Ground Water, *Handbook of Bioremediation*, Lewis Publishers, Boca Raton, FL.
- Borden, R.C., and Bedient, P.B., 1986. Transport of dissolved hydrocarbons influenced by oxygen limited biodegradation - theoretical development, *Water Resources Research*, vol. 22, no. 13, p. 1973-1982.

- Borden, Robert C., Gomez, Carlos A., and Becker, Mark T., 1995. Geochemical indicators of intrinsic bioremediation, *Ground Water*, vol. 33, no. 2, p. 180-189.
- Bouwer, E.J., 1992. Bioremediation of Subsurface Contaminants, *Environmental Microbiology*, Mitchell, R., ed., Wiley-Liss, New York, New York.
- Bouwer, E.J., 1994. Bioremediation of chlorinated solvents using alternate electron acceptors, *Handbook of Bioremediation*, Lewis Publishers, Boca Raton, FL.
- Bouwer, H., 1989, The Bouwer and Rice slug test - an update: *Ground Water*, v. 27, no. 3, p. 304-309.
- Bouwer, H., and Rice, R. C. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resources Research*, v. 12, no. 3, p. 423-428.
- Brown, R.A., Dey, J.C. and McFarland, W.E., 1991a. Integrated site remediation combining groundwater treatment, soil vapor extraction, and bioremediation, *In Situ Bioreclamation: Application and Investigation for Hydrocarbons and Contaminated Site Remediation*, Eds., R.E. Hinchey and R. F. Olfenbuttel, Butterworth-Heinemann. p. 444-449.
- Brown, R.A., et al., 1991b. The use of aeration in environmental cleanups, *Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection, and Restoration*, Houston, Texas. p. 265-279.
- Buscheck, T.E., K.T. O'Reilly, and S.N. Nelson. 1993. Evaluation of Intrinsic Bioremediation at Field Sites: Proceedings, Petroleum Hydrocarbons, and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration, pp. 367-381. National Ground Water Association/API. Houston, TX.
- Buscheck, T.E., and Alcantar, C.M., 1995. Regression techniques and analytical solutions to demonstrate intrinsic bioremediation, *In Situ and On-Site Bioreclamation*, The Third International Symposium. Sponsored by Battelle, accepted for presentation April 1995.
- Chapelle, F.H., 1993. *Ground-water Microbiology and Geochemistry*. John Wiley and Sons, Inc., New York, NY.
- Chapelle, F.H., 1994. Assessing the Efficiency of Intrinsic Bioremediation, *In Proceedings of the Symposium on Intrinsic Bioremediation of Ground Water*, August 30 - September 1, 1994: US Environmental Protection Agency, p. 171.
- Chapelle, F.H., Bradley, P.M., Lovley, D.R., and Vroblesky, D.A., 1996. Measuring Rates of Biodegradation in a Contaminated Aquifer Using Field and Laboratory Methods. *Ground Water*, v. 34, no. 4, p. 691-698.
- Chiang, C.Y., Salanitro, H.P., Chai, E.Y., Colthart, H.D., and Klein, C.L., 1989. Aerobic biodegradation of benzene, toluene, and xylene in a sandy aquifer - data analysis and computer modeling, *Ground Water*, vol. 27, no. 6, p. 823-834.

- Colquhoun, Dinald J., 1969, Geomorphology of the Lower Coastal Plain of South Carolina. *S.C. Division of Geology Publication MS-15*.
- Cozzarelli, I.M., Eganhouse, R.P., and Baedecker, M.J., 1990. Transformation of monoaromatic hydrocarbons to organic acids in anoxic ground water environment, *Environmental and Geological Water Science*, vol. 16.
- Cozzarelli, I.M., Baedecker, M.J., Eganhouse, R.P., 1994. The geochemical evolution of low-molecular-weight organic acids derived from the degradation of petroleum contaminants in groundwater, *Geochimica et Cosmochimica Acta*, vol. 58, no. 2, p. 863-877.
- Davis, J.W., Klier, N.J., and Carpenter, 1994. Natural biological attenuation of benzene in ground water beneath a manufacturing facility, *Ground Water*, vol. 32, no. 2, p. 215-226.
- Detachment 3, 3rd Weather Wing, Charleston AFB. Furnished the temperature, precipitation and other relevant climatic data for the years 1942-1947 and 1949-1981.
- Detachment 3, 15th Weather Squadron, Charleston AFB. Furnished the temperature, precipitation and other relevant climatic data for the years 1949 through 1979.
- Downey, D.C., and Hall, J.F. 1994. *Addendum One to Test Plan and Technical Protocol for a Field Treatability Test for Bioventing - Using Soil Gas Surveys to Determine Bioventing Feasibility and Natural Attenuation Potential*. Prepared for the Air Force Center for Environmental Excellence, Brooks Air Force Base, San Antonio, Texas.
- EA Engineering Science, and Technology, Inc. (EA), 1993. *Installation and Sampling of Four Ground-Water Monitoring Wells at IRP Site ST-27, Charleston Air Force Base, Charleston, South Carolina*. Prepared for U. S. Air Force Center for Environmental Excellence and Charleston Air Force Base.
- Edwards, E.A., and Grbic-Galic, D., 1992. Complete mineralization of benzene by aquifer microorganisms under strictly anaerobic conditions, *Appl. Environ. Microbiol.*, vol. 58, p. 2663-2666.
- Engineering-Science, Inc. 1981. *Installation Restoration Program, Phase I-Records Search, Hazardous Materials Disposal Sites, Myrtle Beach AFB, South Carolina*. Prepared for USAF AFESC/DEV (Tyndall AFB), Florida. October.
- Engineering-Science, Inc. 1983. *Installation Restoration Program, Phase I-Records Search, Charleston AFB, South Carolina*. Prepared for Charleston AFB, USAF AFESC/DEV (Tyndall AFB) and HQ MAC/DDEV (Scott AFB).
- Engineering Science, Inc. 1991. *Interim Bioventing Pilot Test Results Report for IRP Site ST-27, Charleston AFB, South Carolina*. Letter report prepared for the U. S. Air Force Center for Environmental Excellence and Charleston AFB. July.
- Engineering Science, Inc. 1993. *Bioventing, Air Sparging, and Natural Attenuation Modeling: An Integrated Approach to the Remediation of A Petroleum-Contaminated Site*. Paper prepared for the Seventh National Outdoor Action

Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods. May 25-27.

Engineering Science, Inc. 1993a. *Modeling the Dissolution of JP-4 into Groundwater*. Prepared by EPICS 202F, Colorado School of Mines, for Engineering Science, Inc. (Unpublished manuscript.)

Environmental Resources Management, Inc. (ERM), 1990. *Final Technical Report: Installation Restoration Program, Long Term Monitoring Stage 1, Remedial Investigation, Myrtle Beach AFB, South Carolina*. Prepared for Myrtle Beach AFB, USAF AFSC HSD/YAQ (Brooks AFB) and HQTAC/DEEV (Langley AFB).

Fenneman, Hevin M. and Johnson, Douglas W., 1930, Map of Physical Divisions of the United States. US Geological Survey.

Fetter, C.W., 1994. *Applied Hydrogeology*, Macmillian College Publishing Company, New York, New York.

Freeze, R.A., and Cherry, J.A., 1979. *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

General Engineering Laboratories (GEL), 1988. *Hydrogeologic Study Report, Charleston Air Force Base, Charleston County, South Carolina*. Prepared for Charleston AFB and USAF OEHL/TPM (Brooks AFB). July.

Geraghty & Miller, Inc. 1985. *Installation Restoration Program. Phase II Problem Confirmation and Qualification*, Myrtle Beach Air Force Base, Myrtle Beach, South Carolina, Vol. I (Final Report) and II (Appendices). Annapolis, Maryland, January.

Geraghty & Miller Modeling Group, 1994. *AQTESOLV® Aquifer Test Solver*, Version 2.0, Millersville, Maryland, October.

Gibson, D.T., and Subramanian, V., 1984. Microbial degradation of aromatic hydrocarbons, *Microbial Degradation of Organic Compounds*, Ed., D.T. Gibson, Marcel Dekker, Inc., p. 181-252.

Glowacz, M.E. Livingston, C.M., Gorman, C.L. and Clymer, C.R., 1980, *Economic and Environmental Impact of Land Disposal of Wastes in the Shallow Aquifer of the Lower Coastal Plain of South Carolina (3 volumes - Horry County)*. S.C. Dept. Health and Environment Control Ground Water Protection Division.

Godsy, E.M., 1994. Microbiological and geochemical degradation processes, *Symposium on Intrinsic Bioremediation in Ground Water*, Denver, CO. August 30 - September 1, 1994, p.35-40.

Grbic-Galic, D., 1989. Microbial degradation of homocyclic and heterocyclic aromatic hydrocarbons under conditions, *Dev. Ind. Microbiol.*, vol. 30, p. 237-253.

Grbic-Galic, D., 1990. Anaerobic microbial transformation of nonoxygenated aromatic and alicyclic compounds in soil, subsurface, and freshwater sediments,

- Soil Biochemistry*, Eds Bollag, J.M., and Stotzky, G. Marcel Dekker, Inc., New York, NY. p. 117-189.
- Haag, F., Reinhard, M., and McCarty, P.L., 1991, Degradation of toluene and p-xylene in an anaerobic microcosms: Evidence for sulfate as a terminal electron acceptor, *Environ. Toxicol. Chem.*, vol. 10, p. 1379-1389.
- Halliburton NUS Corporation. 1993. *Installation Restoration Program RCRA Facility Investigation Work Plan for Charleston AFB, Charleston, South Carolina*. Prepared for the U. S. Air Force Center for Environmental Excellence and Charleston AFB. July.
- Higgins, I.J., and Gilbert, P.D., 1978. The biodegradation of hydrocarbons, K.W.A. Chator and H.J. Somerville, The Oil Industry and Microbial Ecosystems: Heyden and Sons, London, p. 80-114.
- Hinchee, R.E., Ong, S.K., Miller, R.N., Downey, D.C., and Frandt, R. 1992. *Test Plan and Technical Protocol for a Field Treatability Test for Bioventing*. Prepared for the Air Force Center for Environmental Excellence, Brooks Air Force Base, San Antonio, Texas. January.
- Hvorslev M. J. 1951. Time Lag and Soil Permeability in Ground-Water Observations. United States Corps of Engineers Waterways Experiment Station Bulletin 36 Vicksburg Mississippi 50p.
- Howard, P.H. 1990. *Handbook of Environmental Fate and Exposure Data for Organic Chemicals*, Vol. II: Solvents. Lewis Publishers, Inc. Chelsea, Michigan. 546 PP.
- Howard, P.H., R.S. Boethling, W.F. Jarvis, W.M. Meylan, and E.M. Michalenko. 1991. *Handbook of Environmental Degradation Rates*. Lewis Publishers. Chelsea, Michigan.
- Hutchins, S.R., and Wilson, J.T., 1991. Laboratory and field studies on BTEX biodegradation in a fuel-contaminated aquifer under denitrifying conditions, *In Situ Bioreclamation, Applications and Investigations for Hydrocarbon and Contaminated Site Remediation*, Eds. R.E. Hinchee and R.F. Olfenbuttel. Butterworth-Heinemann. Boston, MA. p. 157-172.
- Isnard, S., and Lambert, S., 1988. Estimating bioconcentration factors from octanol-water partition coefficient and aqueous solubility, *Chemosphere*, vol. 17, no. 1, p. 21-34.
- Jobson, A.F., Cook, F.D., and Westlake, D.W., 1972. Microbial utilization of crude oil, *Applied and Environmental Microbiology*, vol. 23, p. 1082-1089.
- Johnson, P., 1994. Performance monitoring and pilot testing of *in situ* air sparging systems, *Proceedings of the Third AFCEE Environmental Restoration Technology Transfer Symposium*, San Antonio, Texas.
- Johnson, R.L., 1993. Enhancing biodegradation with *in situ* air sparging: a conceptual model, *Air Sparging for Site Remediation*, Robert E. Hicchee, ed., Lewis Publishers.

- Johnson, A.I., 1967. *Specific Yield - Compilation of Specific Yields for Various Materials*, United States Government Printing Office, Washington.
- Kemblowski, M.W., J.P. Salanitro, G.M. Deeley, and C.C. Stanley. 1987. Fate and Transport of Residual Hydrocarbons in Ground Water: A Case Study: In: *Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water Conference*, National Water Well Association and American Petroleum Institute. Houston, Texas. Pp. 207-231.
- Law Environmental, Inc. 1991c. *Remedial Investigation and Feasibility Report for Building 324 - Solvent Vat Drainage System, Myrtle Beach Air Force Base, Myrtle Beach, South Carolina, Final Report*. Kennesaw, Georgia, October.
- Law Environmental, Inc., 1993. *First Draft: Installation Restoration Program (IRP), Multi-Site Stage 2, Remedial Investigation, POL Bulk Fuel Storage Area Data Summary Report*. Prepared for Myrtle Beach AFB, South Carolina and Air Force Center for Environmental Excellence (Brooks AFB, Texas).
- Law Environmental, Inc., 1994. *Installation Restoration Program (IRP), Multi-Site Stage 2, Remedial Investigation, MOGAS Storage Area Corrective Action Plan*. Prepared for Myrtle Beach AFB, South Carolina and Air Force Center for Environmental Excellence (Brooks AFB, Texas).
- Leahy, J.G., and R.R. Colwell. 1990. Microbial degradation of hydrocarbons in the environment, *Microbiological Reviews*, vol. 53, no. 3, p. 305-315.
- Lee, M.D., 1988. *Bioremediation of Aquifers Contaminated with Organic Compounds: CRC Critical Reviews in Environmental Control*. vol. 18. p. 29-89.
- Litchfield, J.H., and Clark, L.C., 1973. Bacterial activities in ground waters containing petroleum products, American Petroleum Institute, Pub. No. 4211.
- Lovley, D.R., and Phillips, E.J.P., 1988. Novel mode of microbial energy metabolism: organic carbon oxidation coupled to dissimilatory reduction of iron or manganese, *Applied and Environmental Microbiology*, vol. 56, no. 6, p. 1472-1480.
- Lovley, D.R., Phillips, E.J.P., and Lonergan, D.J., 1991. Enzymatic versus nonenzymatic mechanisms for Fe(III) reduction in aquatic sediments, *Environmental Science and Technology*, vol. 26, no. 6, p. 1062-1067.
- Lovley, Derek R., Chapelle, Francis H., and Woodward, Joan C., 1994. Use of dissolved H<sub>2</sub> concentrations to determine distribution of microbially catalyzed redox reactions in anoxic groundwater, *Environmental Science and Technology*, vol. 28, no. 7, p. 1205-1210.
- Lyman, W.J., Reehl, W.F., and Rosenblatt, T.A., 1992,. *Handbook of Chemical Property Estimation Methods Environmental Behavior of Organic Compounds*. McGraw-Hill, Inc., New York, NY.
- MacIntyre, W.G., M. Boggs, C.P. Antworth, and T.B. Stauffer. 1993. Degradation Kinetics of Aromatic Organic Solutes Introduced into a Heterogeneous Aquifer: *Water Resources Research*, v. 29, no. 12, p. 4045-4051.

- Mackay, D., and Shiu, W.Y., 1981. A critical review of Henry's Law Constants for chemicals of environmental interest, *Journal of Physical Chemistry Reference Data*, vol. 10, no. 4, p. 1175-1199.
- Malone, D.R., Kao, C.M., and Borden, R.C., 1993. Dissolution and bio restoration of nonaqueous phase hydrocarbons - models development and laboratory evaluation, *Water Resources Research*, vol. 29, no. 7, p. 2003-2213.
- Marley, M.C., Walsh, M.T., and Nangeroni, P.E., 1990. Case study on the application of air sparging as a complimentary technology to vapor extraction at a gasoline spill site in Rhode Island, *Proceedings of HMRCI's 11th Annual National Conference and Exhibition*, Washington, DC, p. 636-640.
- McAllister, Paul M., and Chiang, Chen Y., 1994. A practical approach to evaluating natural attenuation of contaminants in ground water, presented at the USEPA Symposium on Intrinsic Bioremediation of Ground Water, Denver, CO.
- McCarty, P.L., 1972. Energetics of organic matter degradation,. *Water Pollution Microbiology*, p. 91-118, (ed. R Mitchell). Wiley-Interscience.
- McCarty, P.L., and Semprini, L., 1994. ground-water treatment for chlorinated solvents, *Handbook of Bioremediation*, CRC Press, Boca Raton, FL.
- Mehran, M., R. L. Olsen, and B. M. Rector, 1987. *Distribution Coefficient of Trichloroethylene in Soil-Water Systems. Ground Water* 25(3).
- Metcalf and Eddy, Inc. 1993. *Chemical and Physical Characteristics of Crude Oil, Gasoline, and Diesel Fuel: A Comparative Study*. Submitted to Western States Petroleum Association (Sept. 17).
- Michelson, K.D, D.L Kringel, G.L. Ginsberg, and W.H. Koch. 1993. Comparative analysis of two models to estimate vapor intrusion through a building foundation and associated cancer risks. Air & Waste Management association, Denver, CO. June 13.
- Micromedex, Inc., 1995. *Toxicology, Occupational Medicine and Environmental Series (TOMES) Plus Database*, vol. 26. Denver, Colorado.
- Micromedex, Inc., 1996. *Toxicology, Occupational Medicine and Environmental Series (TOMES) Plus Database*, Vol. 28. Denver, Colorado
- Montgomery, J. H. and L. M. Welkom, 1990. *Groundwater Chemicals Desk Reference*. Lewis Publishers, Michigan.
- Mueller, J.G., Chapman, P.J., Blattman, B.O., and Pritchard, P.H., 1994, Isolation and characterization of a fluoranthene-utilizing strain of *Pseudomonas paucimobilis*. *Applied and Environmental Microbiology*, vol. 56, p. 1079-1086.
- New York State Department of Environmental Conservation (DEC), 1993. *Technical Guidance for Screening Contaminated Sediments*, November.
- OSHA, 1989. Title 29, Code of Federal Regulations, Part 1910, Section 1000, Tables Z-1-A and Z-2.

- Parker, K.S., R.C. Sims, and R.R. Dupont. 1990. Transformation of PAHs in soil systems, *Journal of Environmental Engineering*, vol. 116, No. 3, pp. 632-640.
- Parsons Engineering Science, Inc., 1994, Work Plan for a Corrective Action Study in Support of Intrinsic Remediation for Ground Water POL Bulk Fuel Storage Area, IRP Site SS-03, Myrtle Beach Air Force Base, December.
- Parsons Engineering Science, Inc., 1994, Work Plan for a Corrective Action Study to Support the Risk-Based Approach to Remediation, MOGAS Site, Myrtle Beach Air Force Base, December.
- Parsons Engineering Science, Inc., 1995, Corrective Action Study to Evaluate Intrinsic Remediation for the POL Bulk Fuel Storage Area, Myrtle Beach Air Force Base, December.
- Perry, J.J., 1977. Microbial metabolism of cyclic hydrocarbons and related compounds, *Critical Reviews in Microbiology*, vol., 5, p. 387-412.
- Regesis, 1996. *Oxygen Release Compound, ORC<sup>®</sup>, A Case Study of Oxygen Distribution in an Aquifer*. ORC Technical Bulletin #1v.3a.
- Reinhard, M., 1994. In-Situ bioremediation technologies for petroleum-derived hydrocarbons based on alternate electron acceptors (other than molecular oxygen), *Handbook of Bioremediation*,. Lewis Publishers, Boca Raton, FL. 1994.
- Reinhard, M., Goodman, N.L., and Barker, J.F., 1984. Occurrence and distribution of organic chemicals in two landfill leachate plumes, *Environ. Sci. Technol.*, vol. 18, no. 12, p. 953-961.
- Salanitro, J.P.. 1993. The role of bioattenuation in the management of aromatic hydrocarbon plumes in aquifers, *Ground Water Monitoring and Remediation*, vol. 13, pp. 150-161.
- Seech, A.G., Marvan, I.J., and Trevors, J.T., 1994. Bioremediation of industrial soils containing chlorinated phenols and polycyclic aromatic hydrocarbons, *Bioremediation of Chlorinated and Polycyclic Aromatic Hydrocarbon Compounds*, Eds., .E. Hincee, A. Leeson, L. Simprini, and S.K. Ong. Lewis Publishers, Ann Arbor.
- Simpkin, T.J., and Gresbrecht, G., 1994. Bioremediation of polycyclic aromatic hydrocarbons in sediments from and industrial complex, *Bioremediation of Chlorinated and Polycyclic Aromatic Hydrocarbon Compounds*, Eds., .E. Hincee, A. Leeson, L. Simprini, and S.K. Ong. Lewis Publishers, Ann Arbor.
- South Carolina Department of Health and Environmental Control. 1993. *Water Classifications and Standards*, Regulation 61-68. May 28.
- South Carolina Department of Health and Environmental Control. 1994a. *Ground Water Mixing Zone Guidance Document*. March
- South Carolina Department of Health and Environmental Control. 1995. *Risk-Based Corrective Action for Petroleum Releases*. June.

- Souza, R., 1997. Personal Communication, February 14.
- Stieber, M., K. Böckle, P. Werner, and F.H. Frimmel. 1990. Biodegradation of polycyclic aromatic hydrocarbons (PAH) in the subsurface., F. Arend, M. Hinseveld, and W. J. Van den Brink (Eds.), pp. 473-479. Kluwer Academic Publishers, Netherlands.
- Strack, O.D.L., 1989, *Groundwater Mechanics*: Prentice-Hall, Englewood Cliffs, New Jersey, 732 p.
- Stumm, W. and Morgan, J.J., 1981, *Aquatic Chemistry*. John Wiley & Sons, New York, NY.
- Summers, K., Gherini, S., and Chem, C.. 1980. *Methodology to Evaluate the Potential for Groundwater Contamination from Geothermal Fluid Release*, EPA-600/7-80-117, as modified by U.S. EPA Region IV.
- Target Environmental Services, Inc. 1993. *Soil Gas and Ground Water Survey, Myrtle Beach Air Force Base, South Carolina*. Prepared for Law Environmental, Inc. July.
- Thierrin, J., Davis, G.B., Barber, C., Patterson, B.M., Pribac, F., Power, T.R., and Lambert, M., 1992. Natural degradation rates of BTEX compounds and naphthalene in a sulfate reducing ground water environment, *In-Situ Bioremediation Symposium "92"*, Niagara-on-the-Lake, Ontario, Canada. September 20-24, 1992: In Press.
- US Air Force, 1993. *Preliminary Final Environmental Impact Statement, Disposal and Reuse of Myrtle Beach Air Force Base, South Carolina*. AFCEE/ESE, January.
- USEPA. 1987. *A Compendium of Superfund Field Operations Methods*. Office of Emergency and Remedial Response. EPA/540/P-87/001. (OSWER Directive 9355.0-14)
- USEPA. 1988. *Guidance for Conducting Remedial Investigations and Feasibility Studies (RI/FS) Under CERCLA*. OSWER Directive 9355.3-01.
- USEPA. 1989. *Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual (Part A)*, Interim Final, Publication EPA 540/1-89/002.
- USEPA. 1991. *Human Health Evaluation Manual, Supplemental Guidance: Standard Default Exposure Factors* Office of Solid Waste and Emergency Response Directive 9285.6-03.
- USEPA. 1991c. *FAA Aircraft Emissions Database User's Manual*, November 26, Office of Environment and Energy, AEE - 100.
- USEPA. 1992a. *Guidance for Data Usability in Risk Assessment (Part A)*. Office of Emergency and Remedial Response. Publication 9285.7-09a (April).
- USEPA. 1992b, *Guidelines for Exposure Assessment*; Notice, Federal Register, Vol. 57, No. 104 (Friday, May 29, 1992).

- USEPA. 1992c. Modeling atmospheric dispersion and vapor emissions from land surfaces. Includes emission model developed by Farmer, W., Yang, M.S., and Letey, J., 1980, Land disposal of hexachlorobenzene wastes - controlling vapor.
- USEPA. 1993. Internal Memorandum Discussing Revisions to OMB Circular A-94 on Guidelines and Discount Rates for Benefit-Cost Analysis. June 25.
- USEPA. 1994a. *Health Risk Assessments for Superfund Sites: Fact Sheet. Region VIII Technical Guidance.*
- USEPA. 1994b. *Ecological Risk Assessment Guidance for Superfund: Process for Designing and Conducting Ecological Risk Assessments.* Review Draft. Environmental Response Team. Edison, New Jersey. September.
- USEPA. 1994c. The Hydrocarbon Spill Screening Model (HSSM), Volume I: User's Guide. Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma. April. Publication EPA/600/R-94/039a.
- USEPA Region III. 1996. *Risk-Based Concentration Table Memorandum* from R.L. Smith, Ph.D., EPA Region III Senior Toxicologist. April.
- United States Geologic Survey (USGS), 1958, 7.5 Minute Topographic Quadrangle Map of Ladson, South Carolina.
- van Genuchten, M. Th., and Alves, W.J., 1982. Analytical solutions of the one-dimensional convective-dispersive solute transport equation, U.S. Salinity Laboratory, Riverside, California.
- Versar, Inc., 1992. *Installation Restoration Program, Phase II-Remedial Investigation/Feasibility Study Report, Stage 2, Charleston AFB, South Carolina.* Prepared for HQ MAC/DEEV (Scott AFB) and Charleston AFB. April (Final Draft).
- Verschueren, K., 1983. *Handbook of Environmental Data on Organic Chemicals*, Van Nostrand Reinhold Co., New York, New York.
- Walker, J.D., Colwell, R.R., and Petrakis, L., 1976. Biodegradation rates of components of petroleum. *Canadian Journal of Microbiology*, vol. 22, p. 1209-1213.
- Walton, W.C., 1988, Practical Aspects of Groundwater Modeling: National Water Well Association, Worthington, Ohio, 587 p.
- Weidemeier, T.H., Downey, D.C., Wilson, J.T., Kampbell, D.H., Miller, R.N., and Hansen, J.E. 1995. *Technical Protocol for Implementing the Intrinsic Remediation (Natural Attenuation) with Long-term Monitoring Option for Dissolved-phase Fuel Contamination in Ground Water.* Prepared by the Air Force Center for Environmental Excellence, Brooks Air Force Base, San Antonio, Texas.
- Wilson, B.H., Smith, G.B., and Rees, J.F., 1986. Biotransformations of selected alkylbenzenes and halogenated aliphatic hydrocarbons in methanogenic aquifer material: a microcosm study, *Environmental Science and Technology*, 20(10):997-1002.

- Wilson, B.H., Bledsoe, B., and Kampbell, D., 1987. Biological processes occurring at an aviation gasoline spill site, R.C. Averett and D.M. McKnight editors, *Chemical Quality of Water and the Hydrologic Cycle*. Lewis Publishers, Chelsea, Michigan, p.125-137.
- Wilson, B.H., Wilson, J.T., Kampbell, D.H., Bledsoe, B.E., and Armstrong, J.M., 1990. Biotransformation of monoaromatic and chlorinated hydrocarbons at an aviation gasoline spill site, *Geomicrobiology Journal*, 8:225-240.
- Young, L.Y., 1984. Anaerobic degradation of aromatic compounds, *Microbial Degradation of Aromatic Compounds*, Ed. Gibson, D.R., ed.: Marcel-Dekker, New York.
- Zobell, C.E., 1946. Action of microorganisms on hydrocarbons, *Bacterial Review*. vol. 10, p. 1-49.